The color of X-rays

Enrico Junior Schioppa

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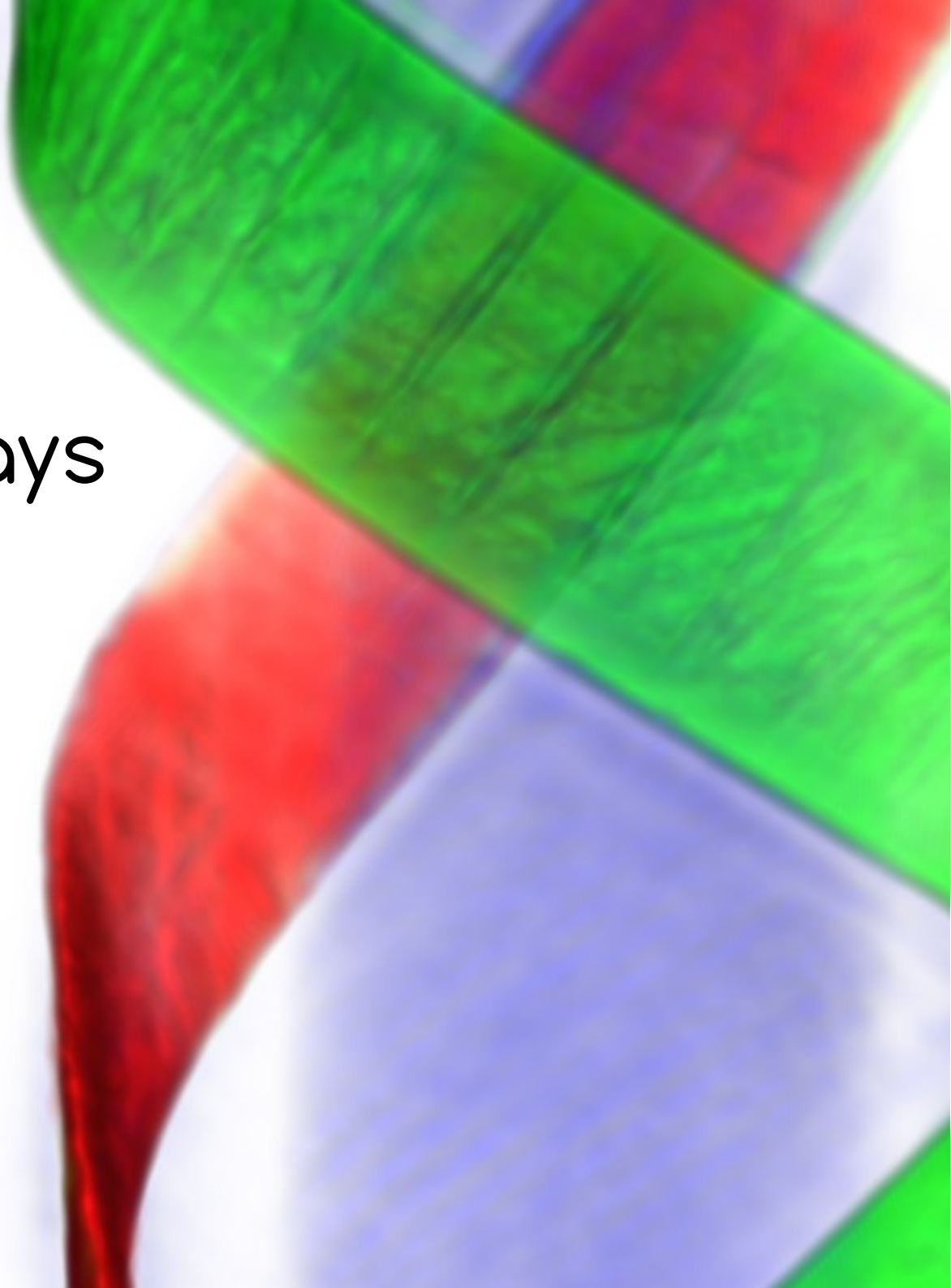


The color of X-rays

Spectral X-ray computed tomography using energy sensitive pixel detectors

ACADEMISCH PROEFSCHRIFT

ter verkrijging van de graad van doctor
aan de Universiteit van Amsterdam
op gezag van de Rector Magnificus
prof. dr. D.C. van den Boom
ten overstaan van een door het college voor promoties ingestelde
commissie, in het openbaar te verdedigen in de Aula der
Universiteit

Universiteit van Amsterdam

Promotiecommissie:

Promotor:	prof. dr. ir. E.N. Koffeman
Co-promotor:	dr. J. Visser
Overige Leden:	prof. dr. S.C.M. Bentvelsen
	dr. A.P. Colijn

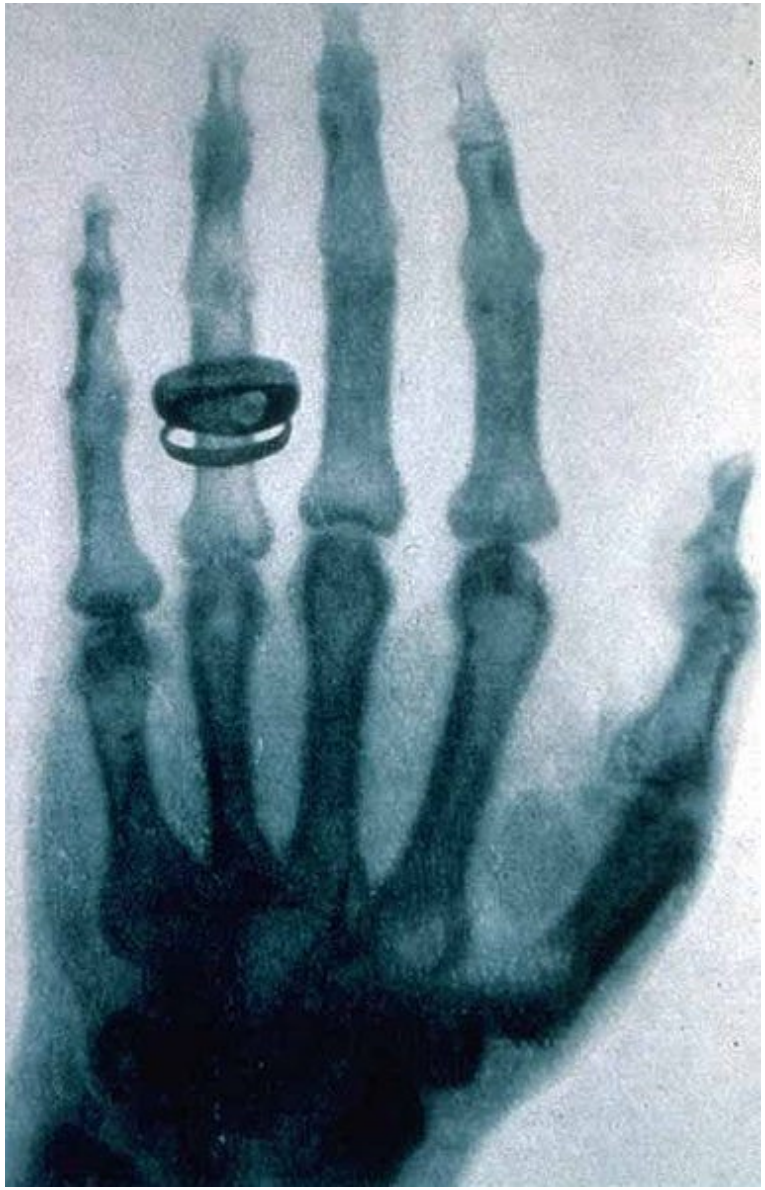
NIKHEF

This work is part of the research program of the Foundation for Fundamental Research on Matter (FOM), which is part of the Netherlands Organization for Scientific Research (NWO). It was carried out at the National Institute for Subatomic Physics (Nikhef) in Amsterdam, the Netherlands. The research has been supported by the Dutch Technology Foundation (STW), which is the applied science division of NWO, and the Technology Programme of the Ministry of Economic Affairs, Project OTP 11956.

ISBN: 978-90-8891-983-1

Cover design by Enrico Junior Schioppa © 2014
Typeset by LaTeX
Printed by: Proefschriftmaken.nl || Uigeverij BOXPress
Published by: Uitgeverij BOXPress, 's-Hertogenbosch

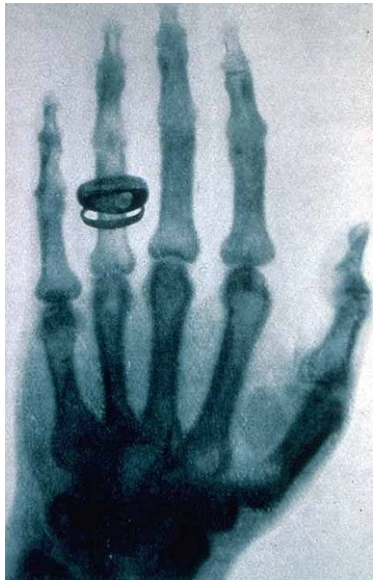
X-ray imaging : how it all started



- X-rays absorbed in the hand
- Count how many “survive”

Radiograph of a hand taken by Wilhelm Röntgen's during a public lecture

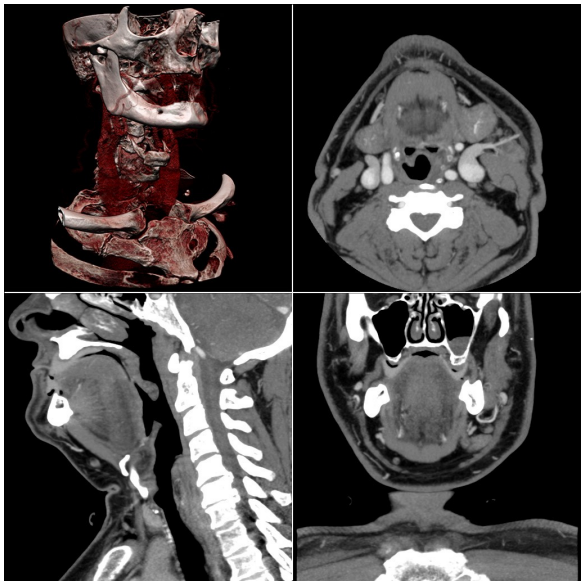
Very short history of X-ray imaging



1896

Radiography

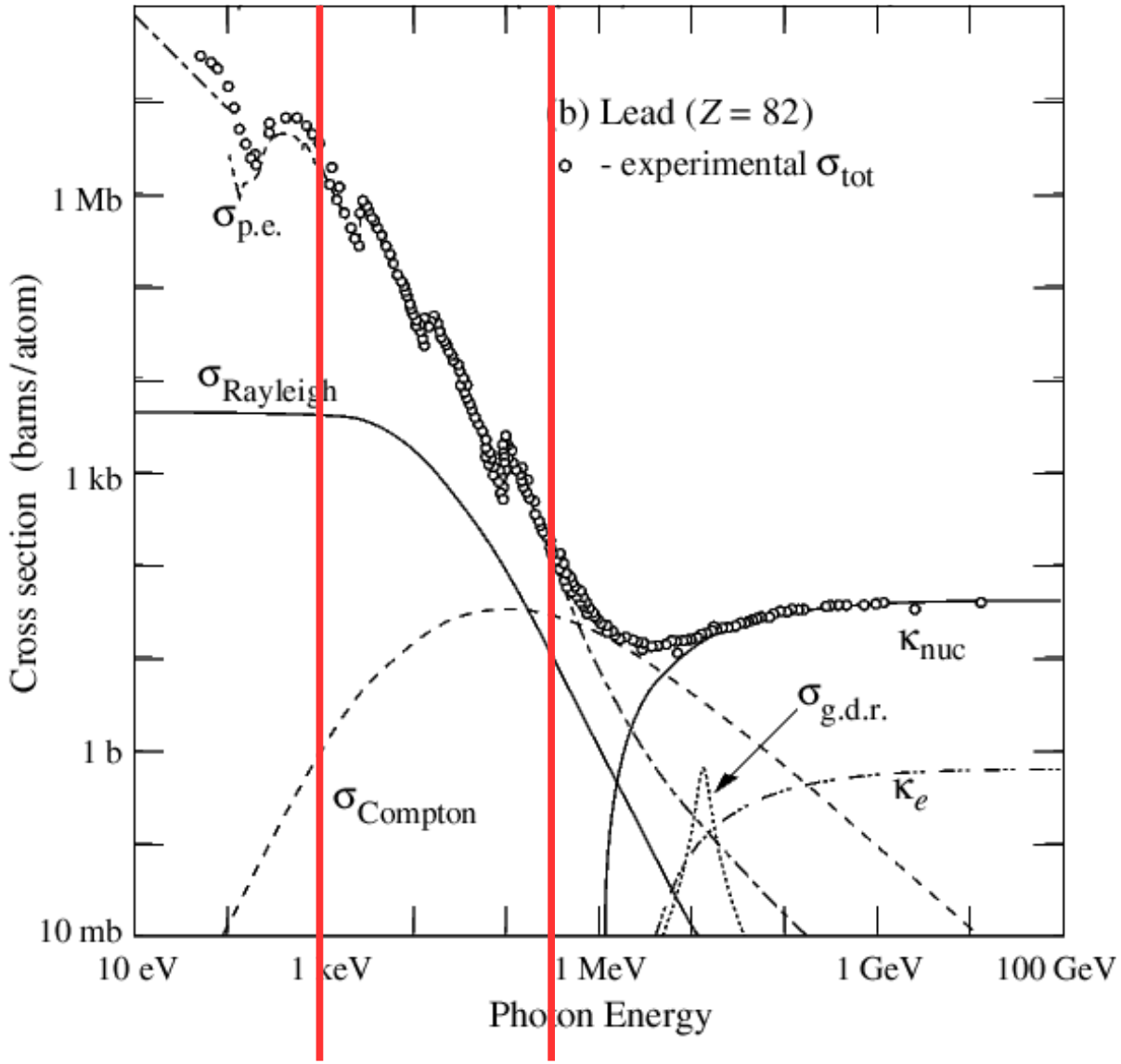
Dual energy



Computed Tomography (CT)

Resolution ~ 0.1-0.2 mm at best
(cannot focus X-rays!)

Interaction of photons with matter



X-ray range → Photoelectric effect

All energy released!

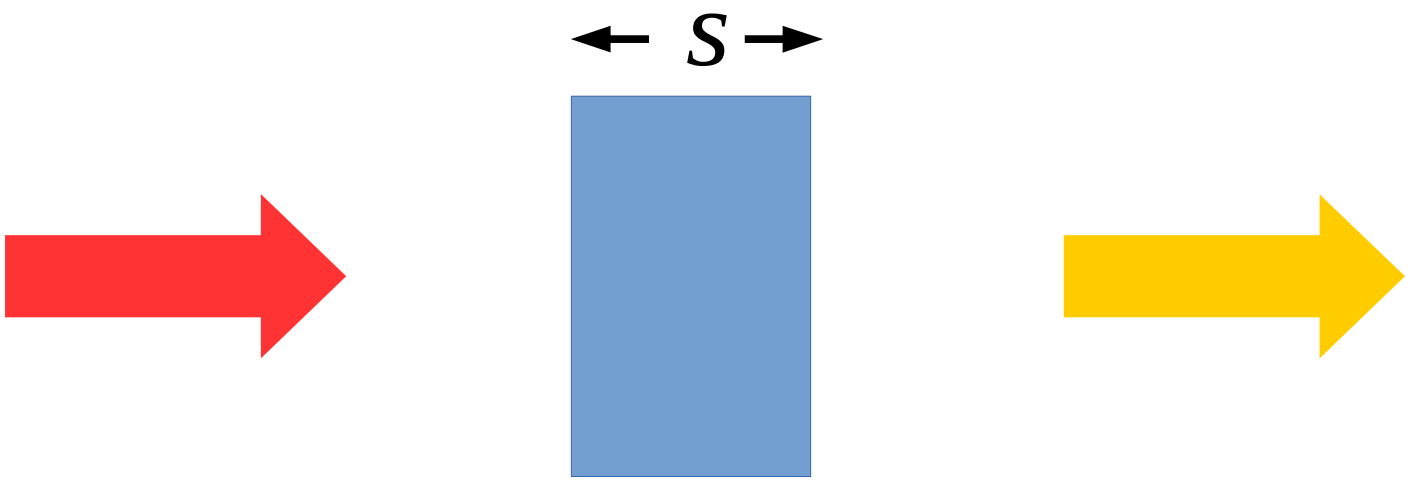
It's all a matter of survival chance

Number of zebras
that DON'T make it

$\propto$

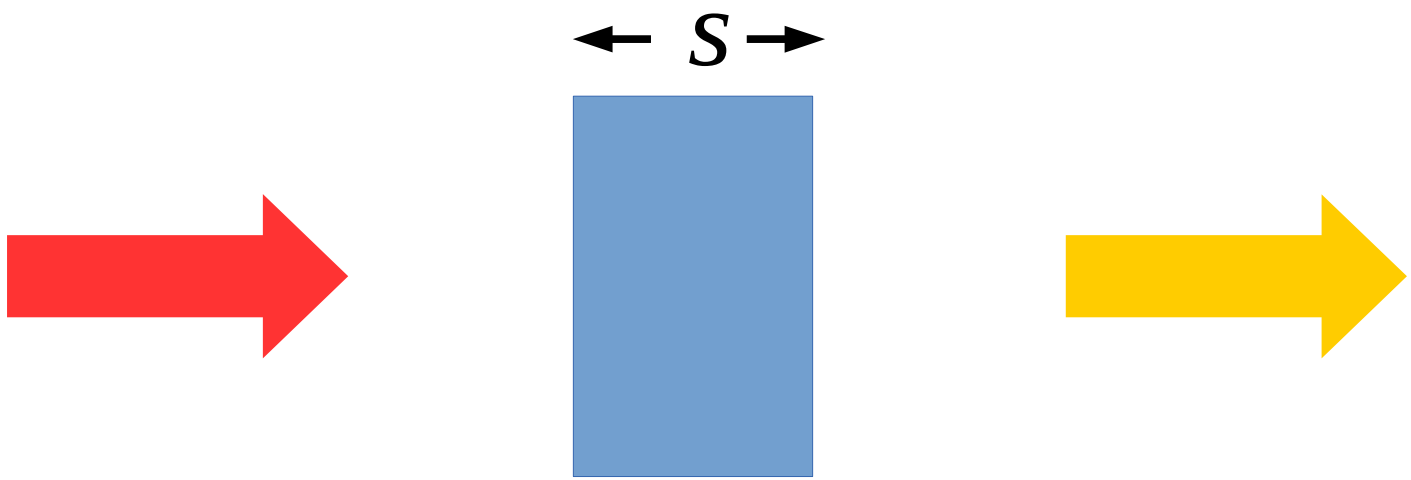
- Number of zebras
- Distance
- Dangerousness

Photon attenuation



I_0 μ $I = I_0 - \Delta I$

Photon attenuation

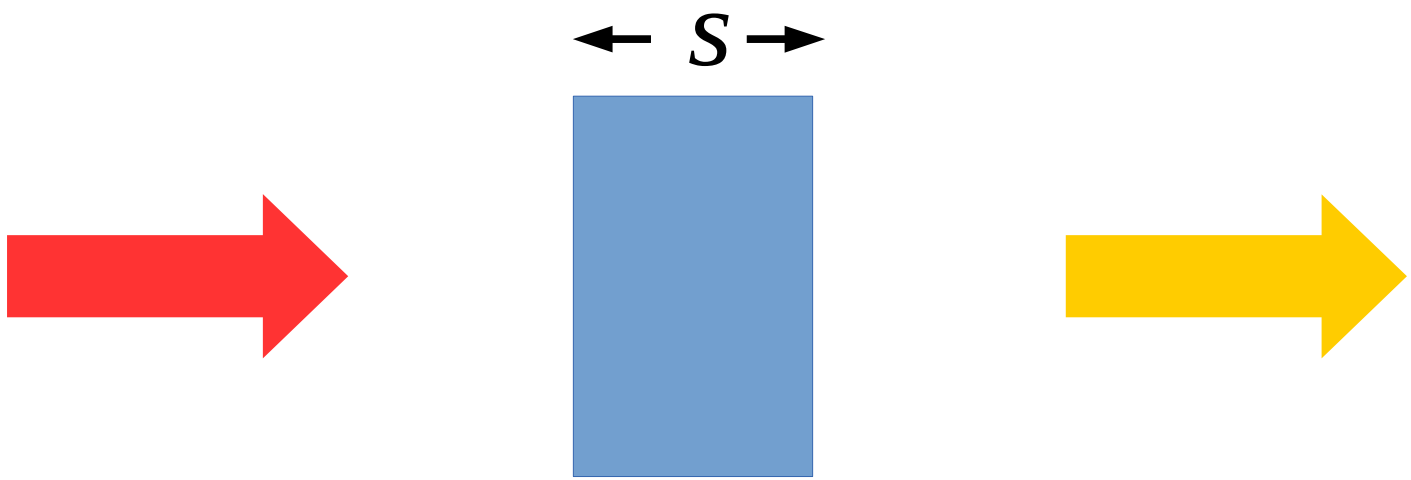


I_0 μ $I = I_0 - \Delta I$

$$\delta I = -\mu I \delta s$$

$$[\mu] = [s^{-1}]$$

Photon attenuation



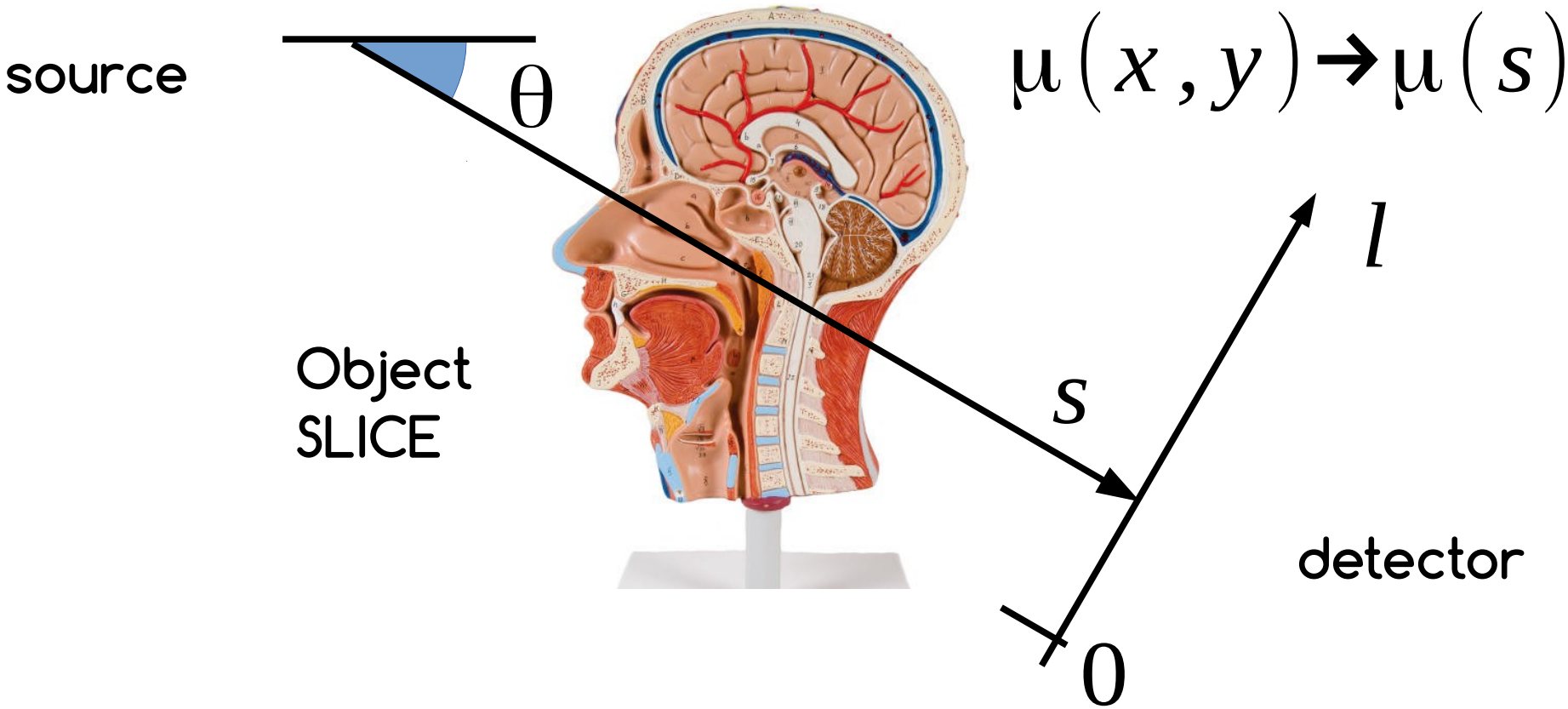
I_0 μ $I = I_0 - \Delta I$

$$\delta I = -\mu I \delta s$$

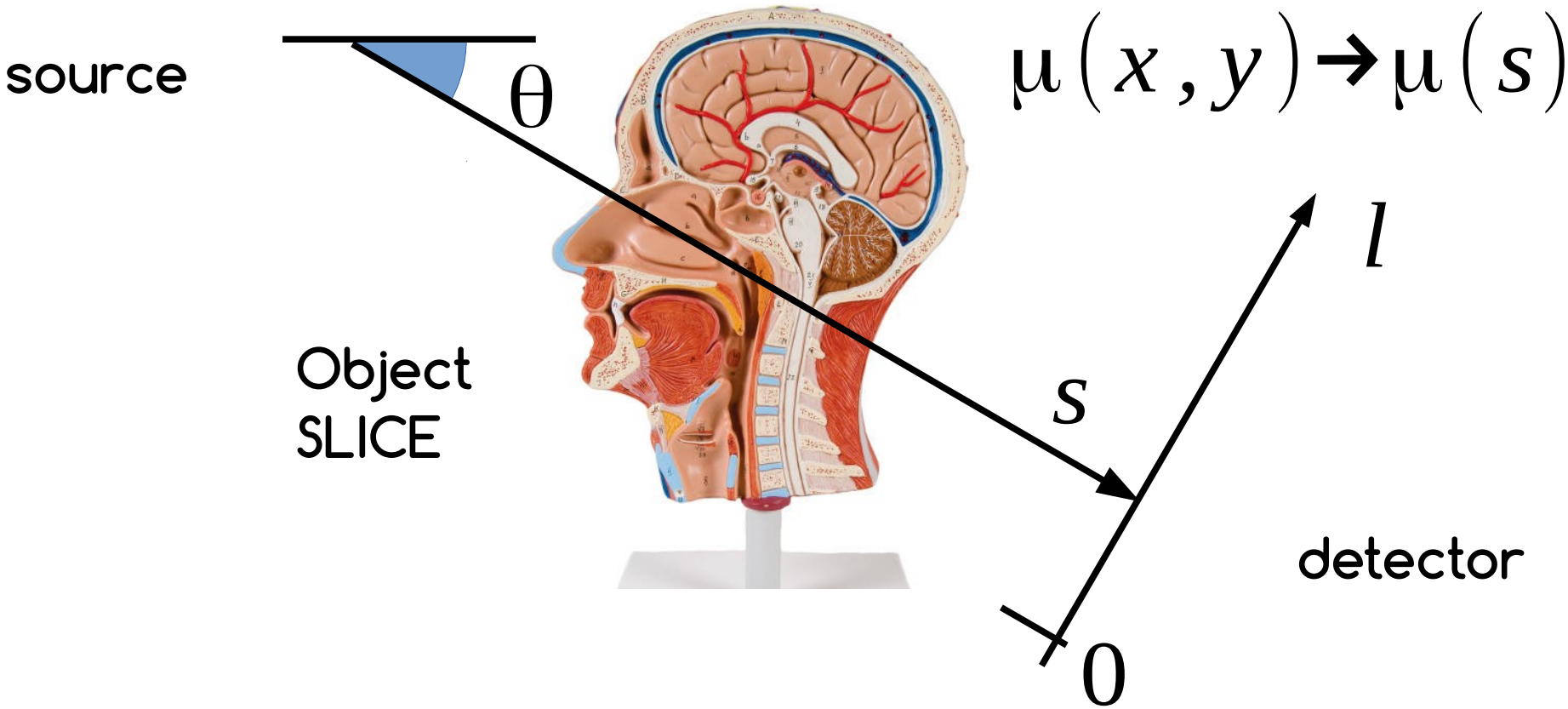
$$[\mu] = [s^{-1}]$$

$$I = I_0 e^{-\mu s}$$

Integral along a ray path

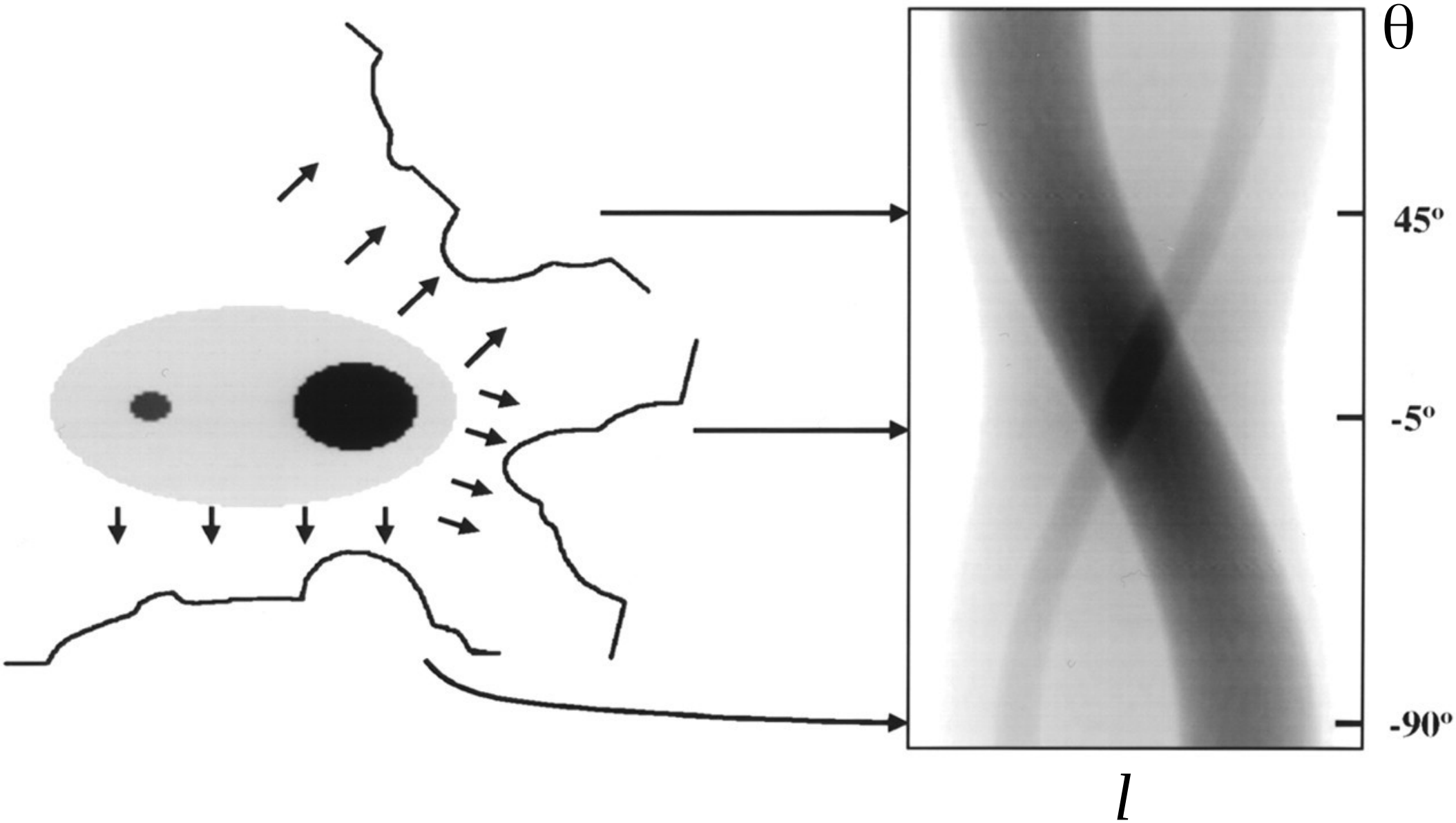


Integral along a ray path



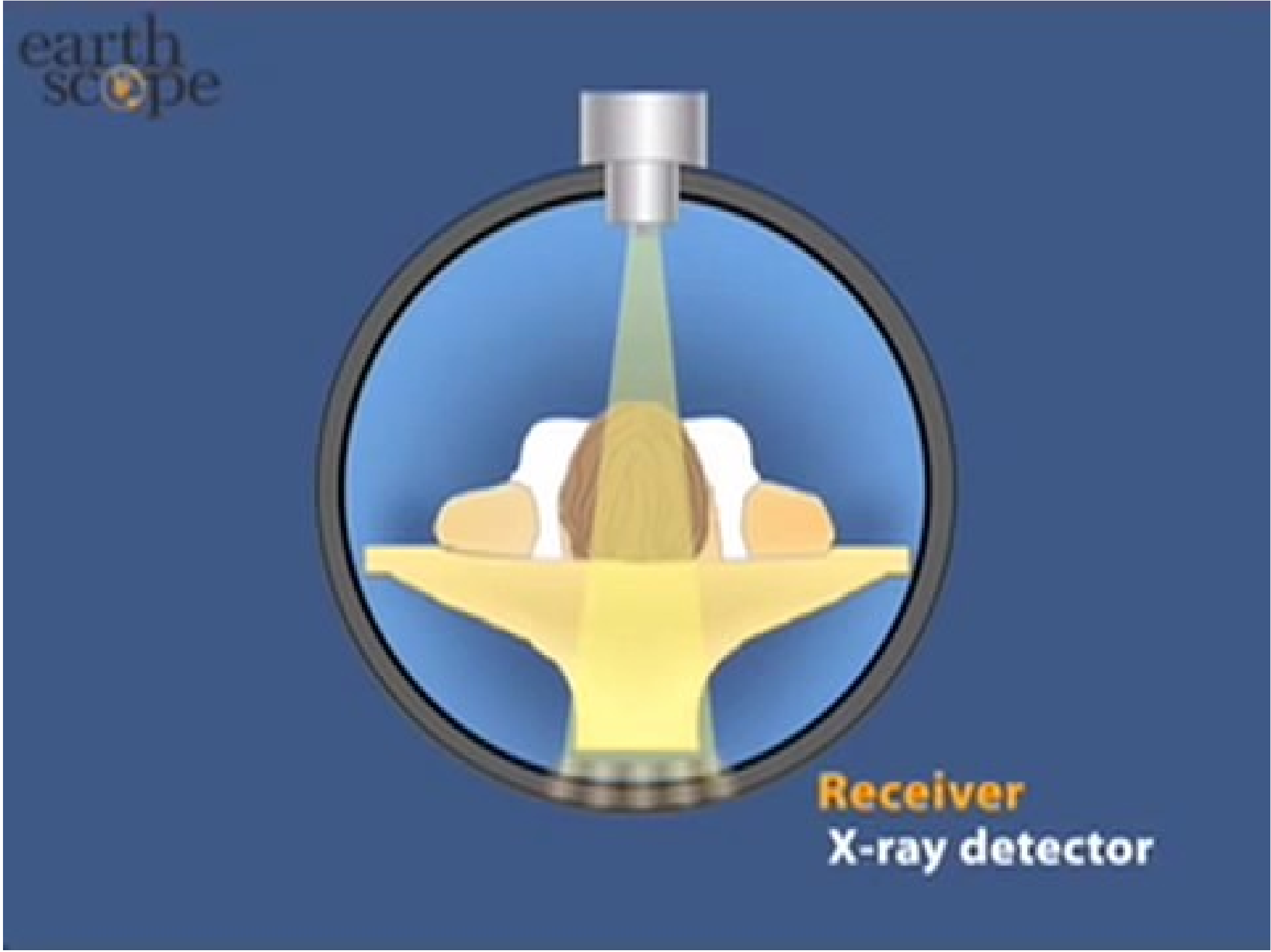
$$I_{l,\theta} = I_0 e^{-\int_{l,\theta} \mu(s)\,ds}$$

Sinograms



The sinogram contains information about the object slice

Quick introduction to Computed Tomography (CT)


earth scope
Receiver
X-ray detector

The CT image reconstruction problem

Set of X-ray images
at different angles

3D image

CT reconstruction as a set of linear equations

$$I_{l,\theta} = I_0 e^{-\int_{l,\theta} \mu(s)\,ds} \quad \Rightarrow \quad \int_{l,\theta} \mu(s)\,ds = -\log \frac{I_{l,\theta}}{I_0}$$

CT reconstruction as a set of linear equations

$$I_{l,\theta} = I_0 e^{-\int_{l,\theta} \mu(s)\,ds} \quad \Rightarrow \quad \int_{l,\theta} \mu(s)\,ds = -\log \frac{I_{l,\theta}}{I_0}$$

$$I_0 \qquad e^{-\int_{l,\theta} \mu(s)\,ds} \qquad = I_{l,\theta}$$

CT reconstruction as a set of linear equations

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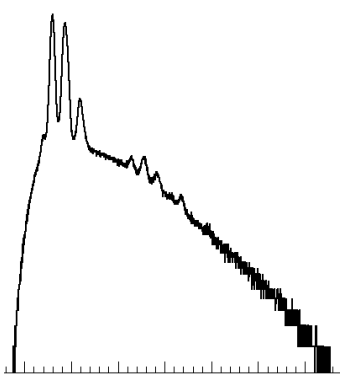
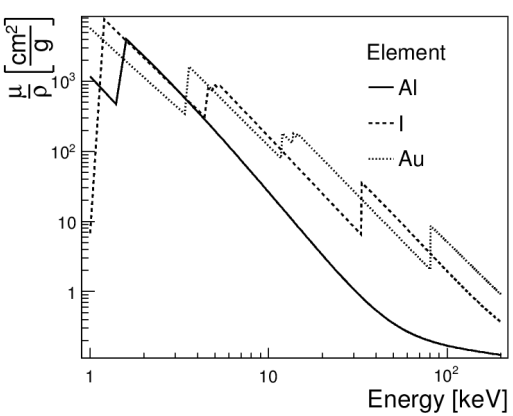
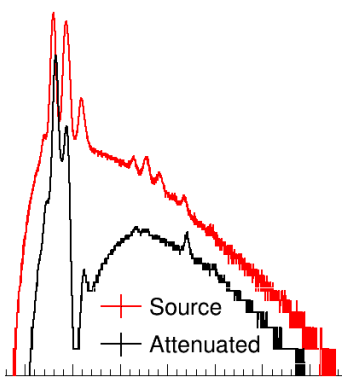


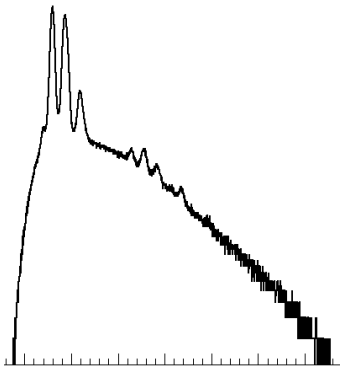


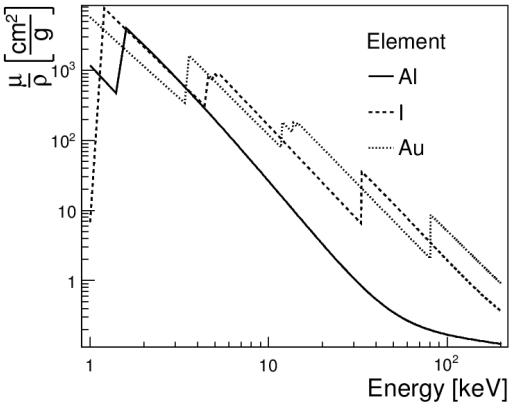


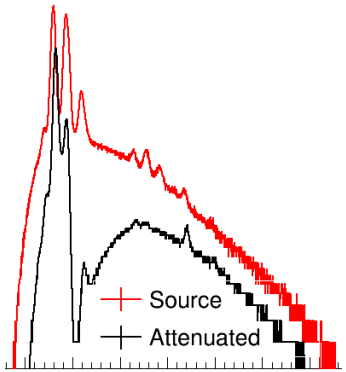
CT reconstruction as a set of linear equations

$$I_{l,\theta} = I_0 e^{-\int_{l,\theta} \mu(s)\,ds} \quad \Rightarrow \quad \int_{l,\theta} \mu(s)\,ds = -\log \frac{I_{l,\theta}}{I_0}$$

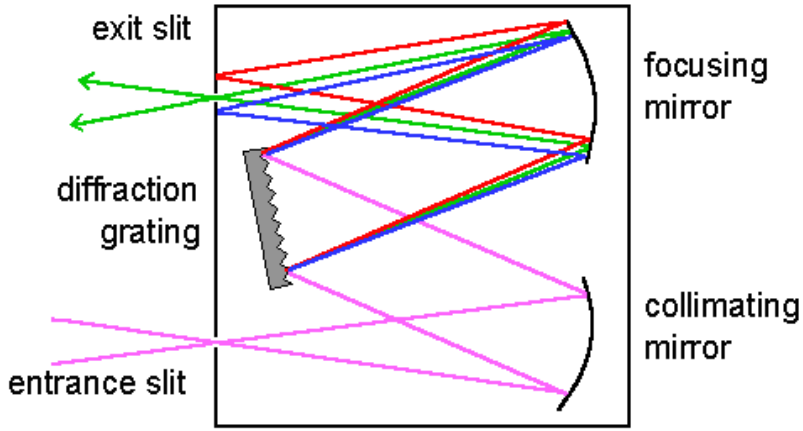
$$I_0(E) \quad e^{-\int_{l,\theta} \mu(s,E)\,ds} \quad = I_{l,\theta}(E)$$



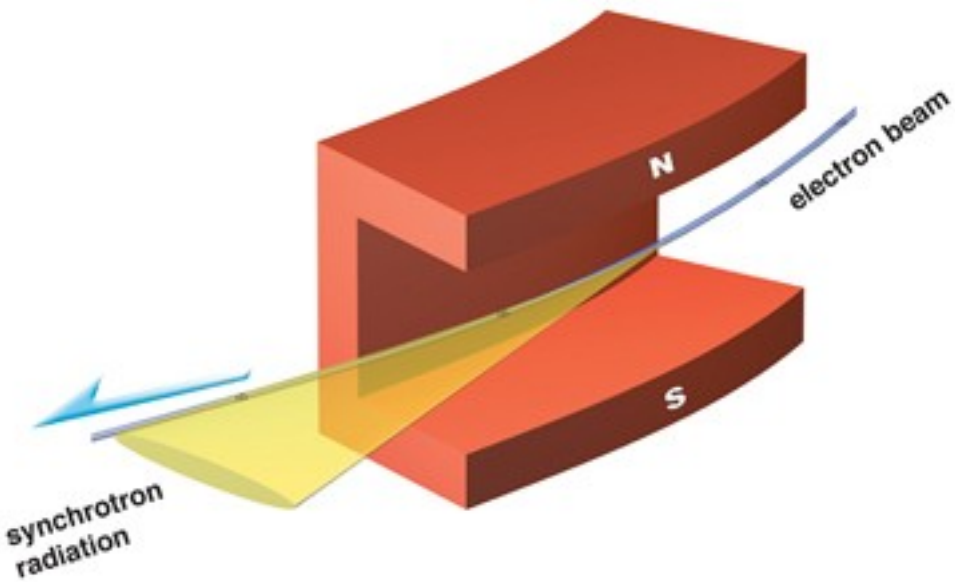




Monochromatic X-ray sources?



Monochromators?



Synchrotrons?

Impractical!

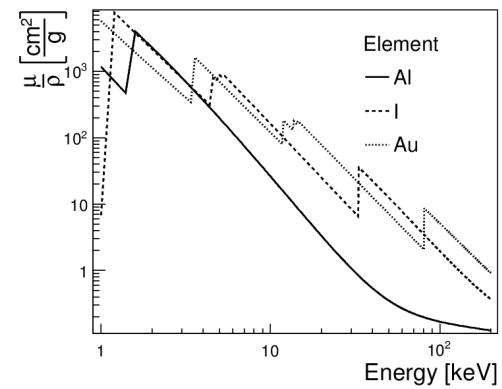
The real CT equations

$$I_0(E)$$

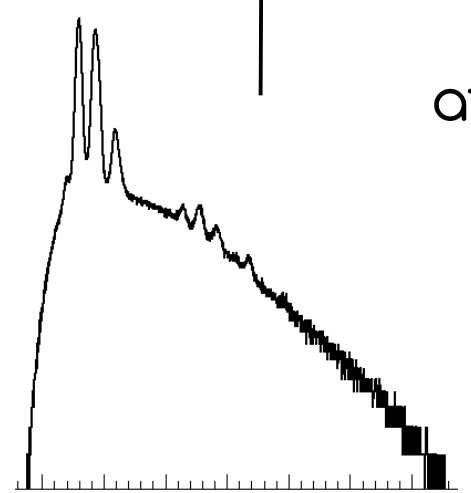
source spectrum

The real CT equations

$$I_0(E)\,e^{-\int_{l,\theta}\mu(s,E)\,ds}$$



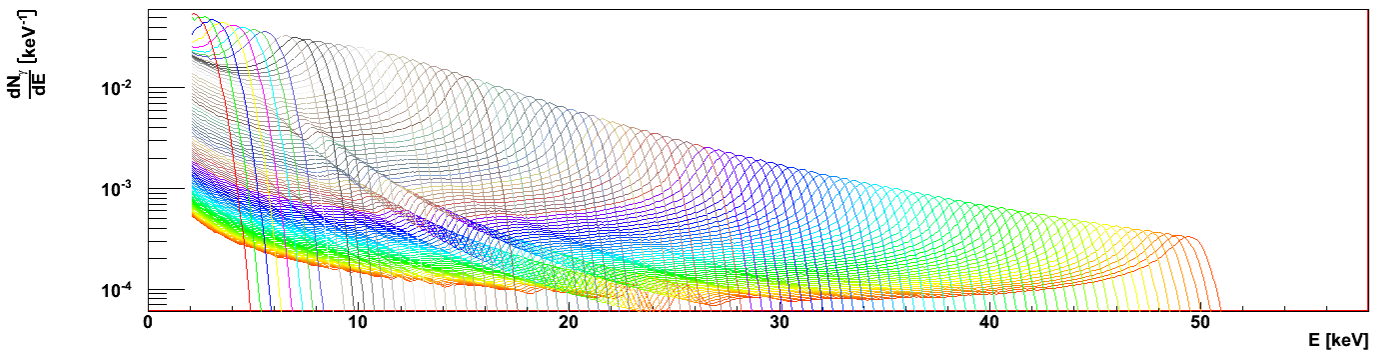
attenuation curves



source spectrum

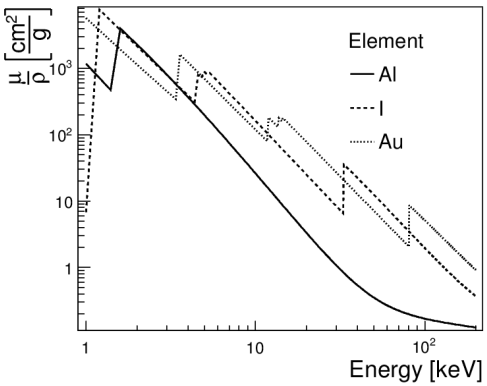
The real CT equations

$$\int_0^{+\infty} dE\, R(E;E')\, I_0(E)\, e^{-\int_{l,\theta} \mu(s,E)\, ds}$$

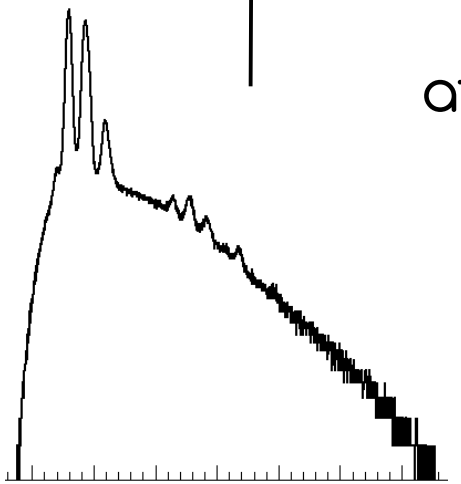


detector response function

Probability that a photon at energy E is detected as having energy E'



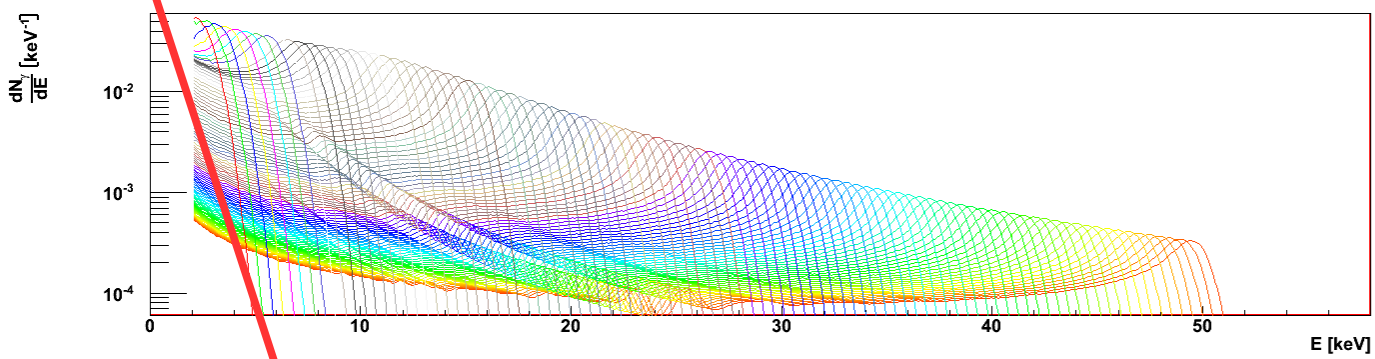
attenuation curves



source spectrum

The real CT equations

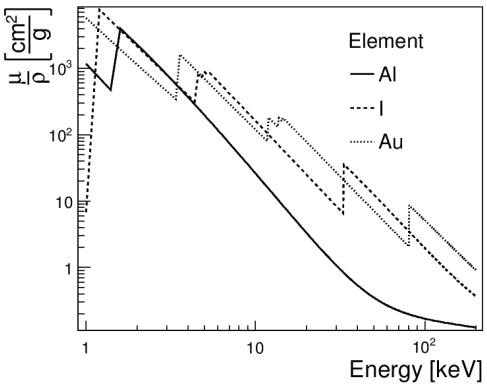
$$N_{l,\theta} = \int_0^{+\infty} dE' \int_0^{+\infty} dE\, R(E;E')\, I_0(E)\, e^{-\int_{l,\theta} \mu(s,E)\, ds}$$



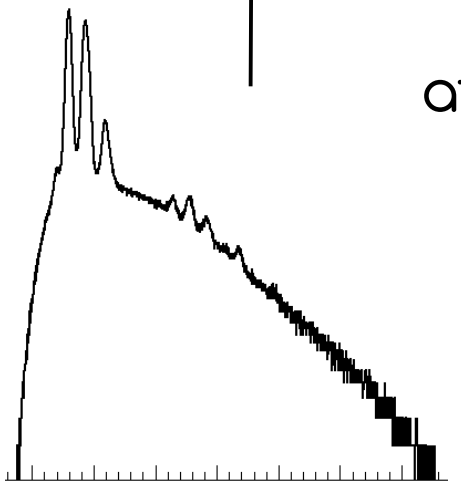
detector response function

Probability that a photon at energy E is detected as having energy E'

One number!

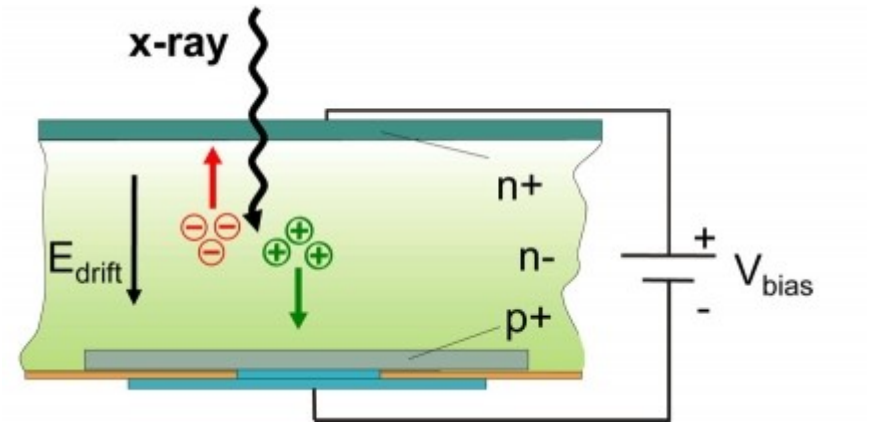


attenuation curves



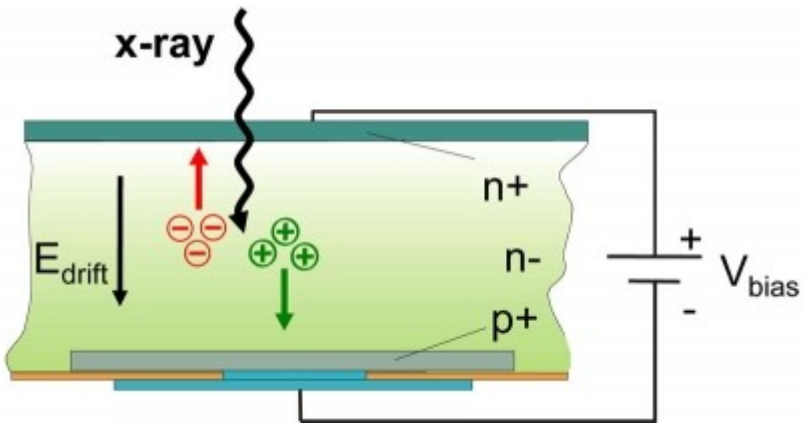
source spectrum

Principle of conventional X-ray detection



Charge ↔ energy

Principle of conventional X-ray detection



Charge ↔ energy

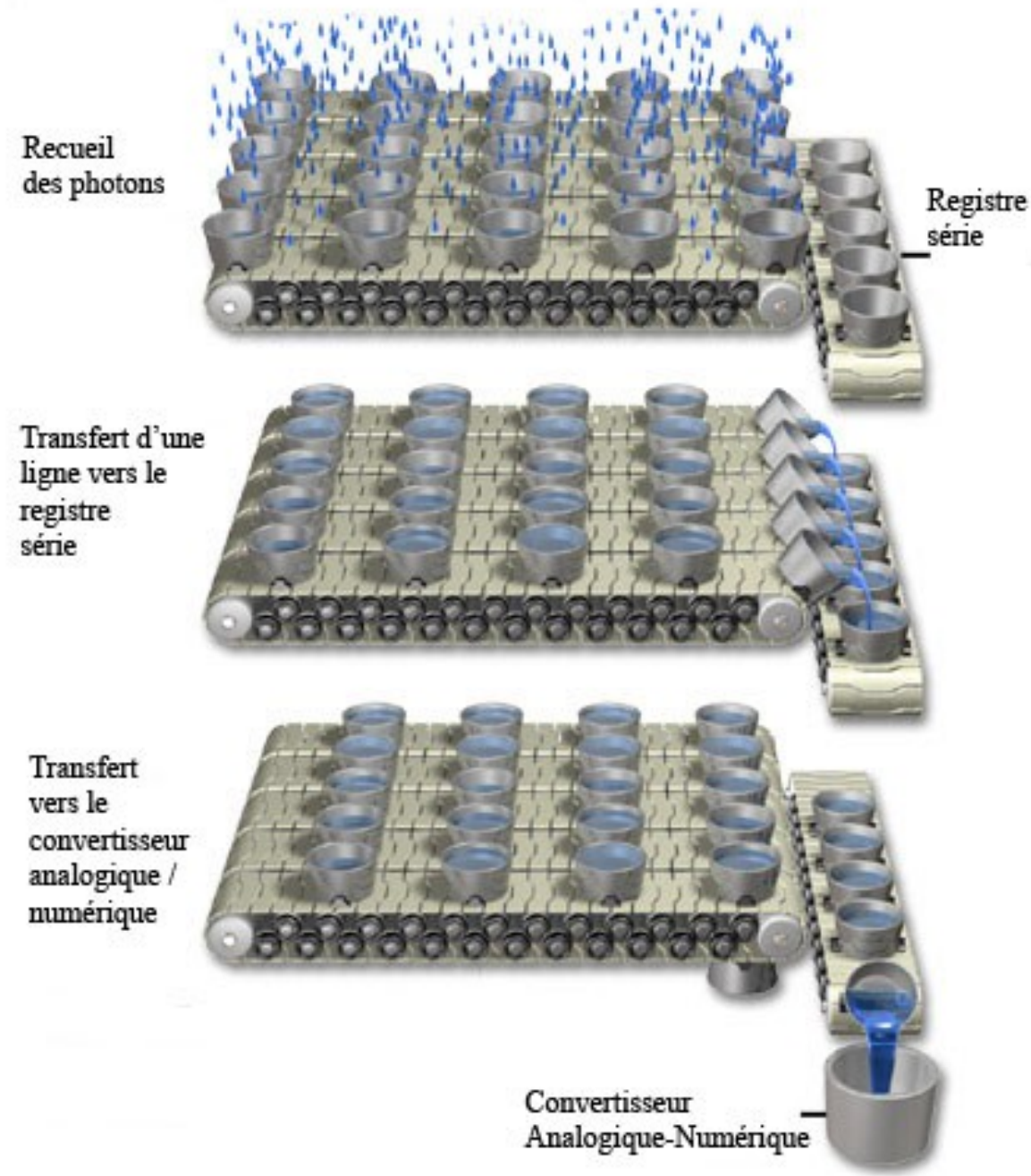
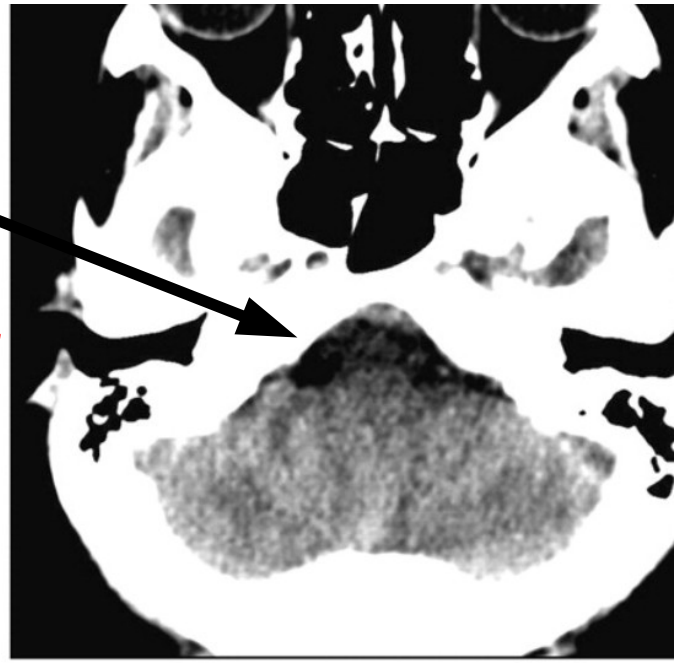


Image artifacts in CT

Some brain missing?

What the heck is going on here?



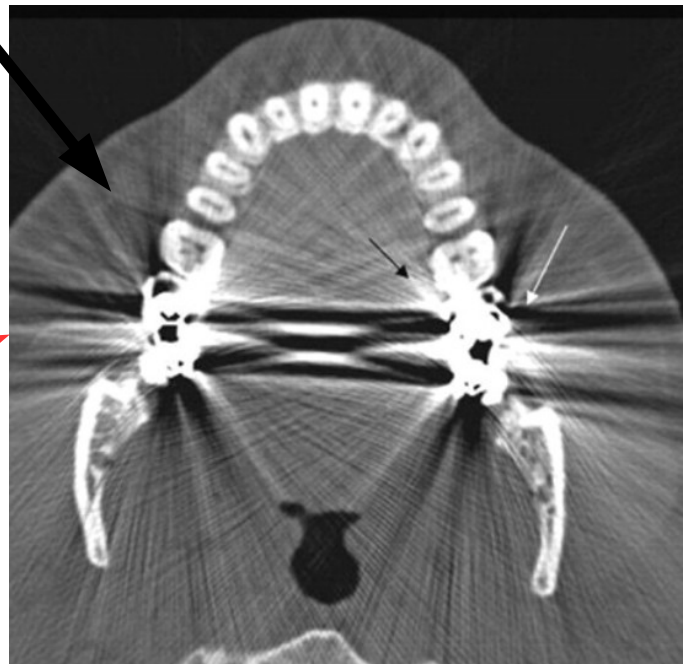
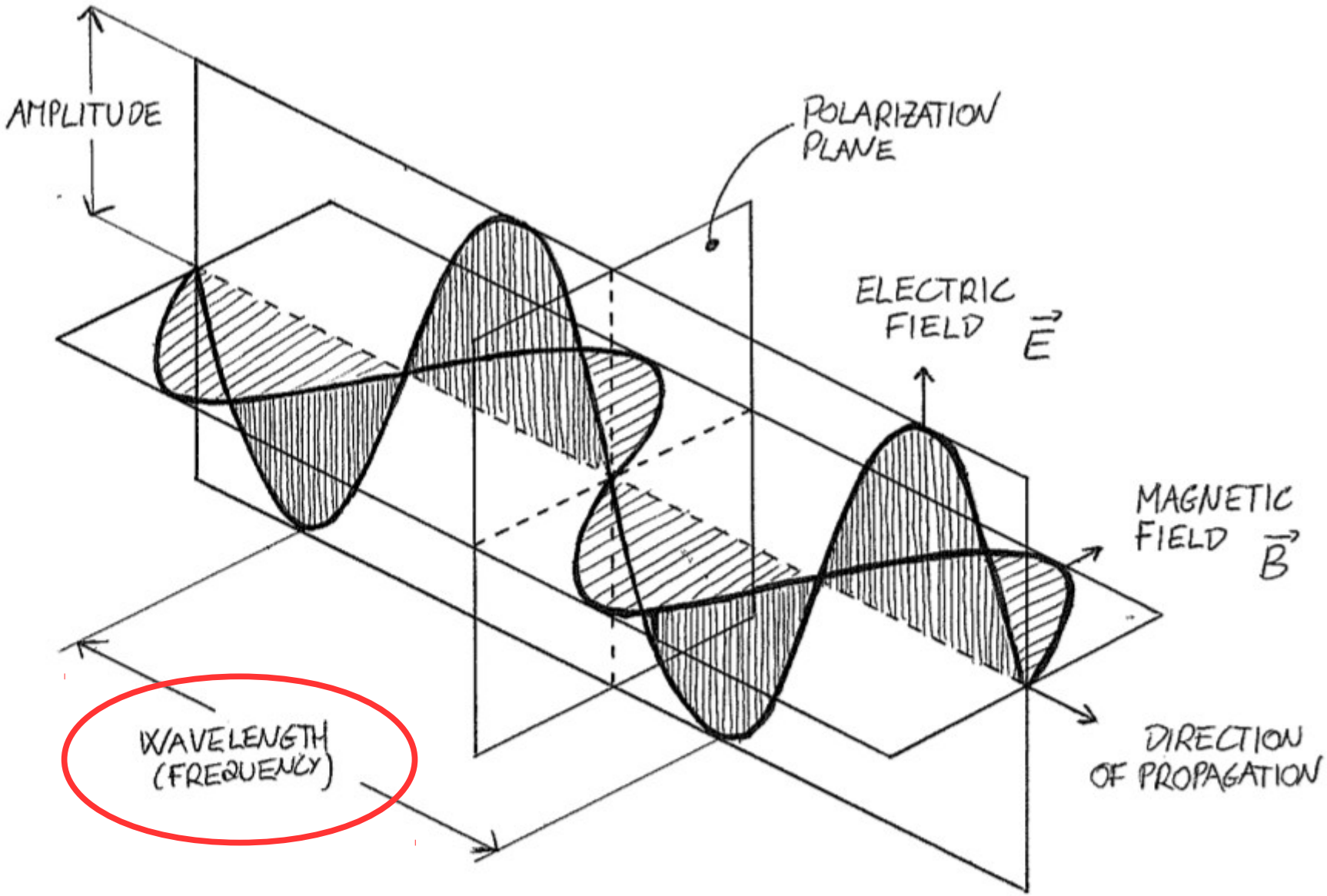


Image credit: R. Popilock, K. Sandrasagaren, L. Harris, and K. A. Kaser. CT Artifact Recognition for the Nuclear Technologist. J. Nucl. Med. Tech., 36(2):79–81, 2008.

Parameters of electromagnetic radiation



An electromagnetic wave

Material decomposition

$$N_{l,\theta} = \int_0^{+\infty} \dots e^{-\int_{l,\theta} \mu(s,E)\, ds}$$

Not linear, but this is the only equation we have

Material decomposition

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$$N_{l,\theta} = \int_0^{+\infty} \ldots e^{-\int_{l,\theta} [\alpha_1 \mu_1(s,E) + \alpha_2 \mu_2(s,E)]\, ds}$$

Material decomposition

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$$N_{l,\theta} = \int_0^{+\infty} \ldots e^{-\int_{l,\theta} [\alpha_1 \mu_1(s,E) + \alpha_2 \mu_2(s,E)]\, ds}$$

$$\begin{cases} N_{l,\theta,t_1} = \int_{t_1}^{+\infty} \ldots e^{-\int_{l,\theta} [\alpha_1 \mu_1(s,E) + \alpha_2 \mu_2(s,E)]\, ds} \\ N_{l,\theta,t_2} = \int_{t_2}^{+\infty} \ldots e^{-\int_{l,\theta} [\alpha_1 \mu_1(s,E) + \alpha_2 \mu_2(s,E)]\, ds} \end{cases}$$

Material decomposition

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$$N_{l,\theta,t} = \int_{t}^{+\infty} \ldots e^{-\int_{l,\theta} \sum_m^M \alpha_m \mu_m(s,E)\, ds} \qquad t = 1, \ldots, M$$

Material decomposition

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Not linear, but this is the only equation we have

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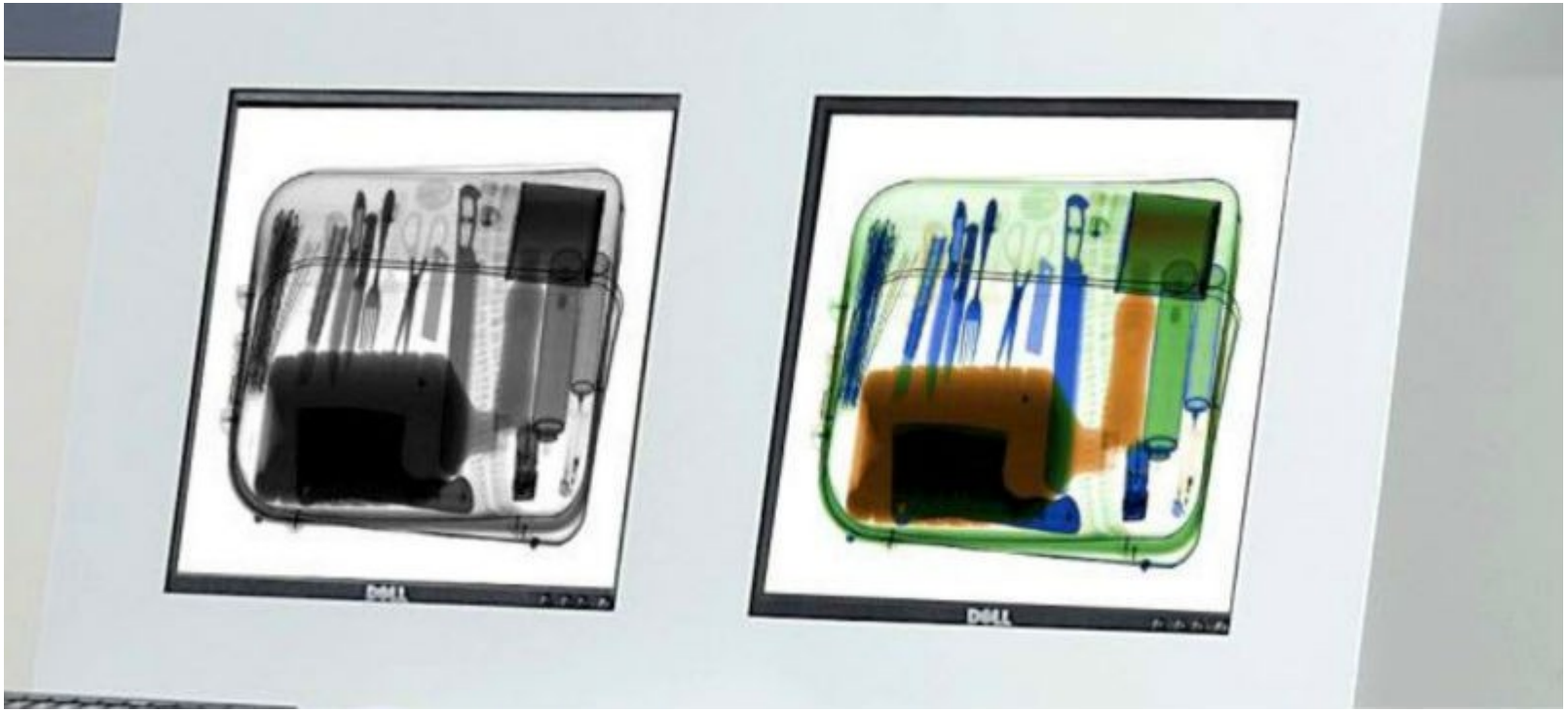
$$N_{l,\theta,t} = \int_t^{+\infty} \ldots e^{-\int_{l,\theta} \sum_m^M \alpha_m \mu_m(s,E)\, ds} \qquad t = 1, \ldots, M$$

Dual energy X-ray imaging



- No 3D information
  → ambiguities

- Two X-ray sources
  → high dose

How to really solve CT?

$$N_{l,\theta,t} = \int_{t}^{+\infty} \ldots R(E, E') \ldots e^{-\int_{l,\theta} \sum_{m}^{M} \alpha_m \mu_m(s, E)\, ds}$$

1 - the threshold trick

2 - the detector response

3 – how do we invert the integral?

How to really solve CT?

$$N_{l,\theta,t} = \int_{t}^{+\infty} \ldots R(E, E') \ldots e^{-\int_{l,\theta} \sum_{m}^{M} \alpha_m \mu_m(s, E)\, ds}$$

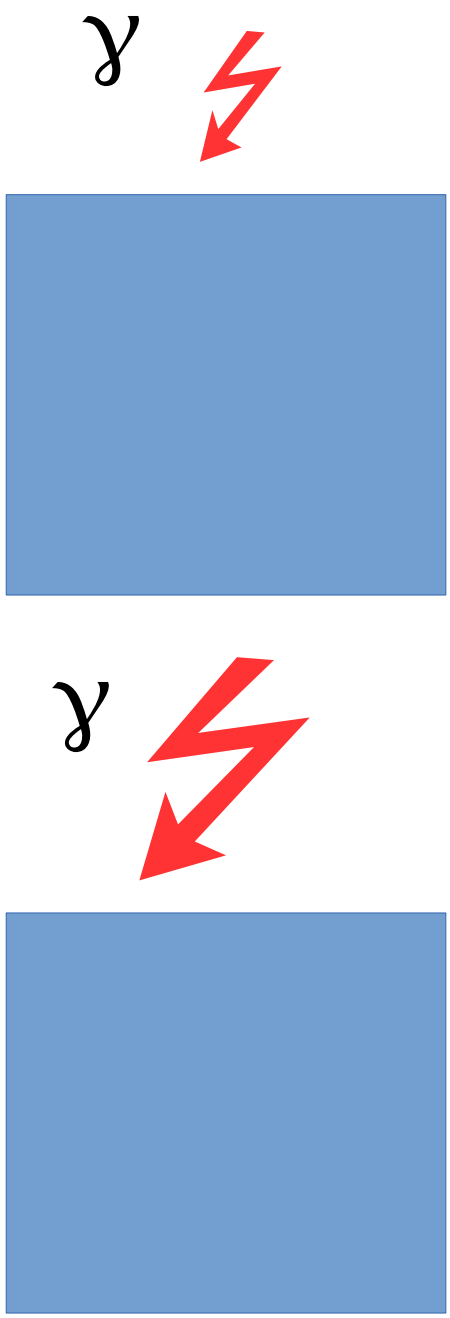
1 - the threshold trick

2 - the detector response

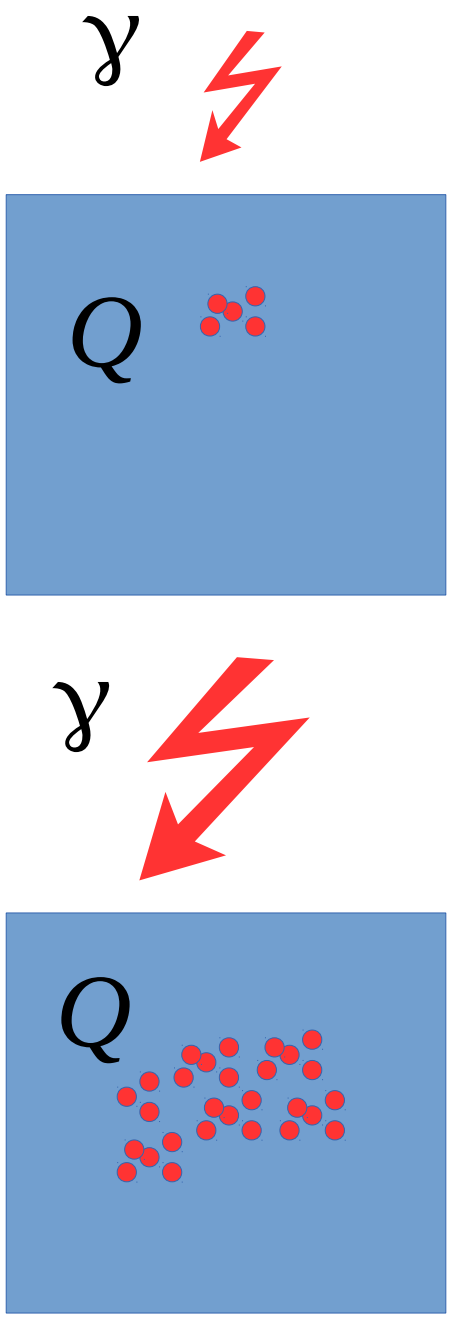
3 – how do we invert the integral?

Spectroscopic (hybrid) pixel detectors

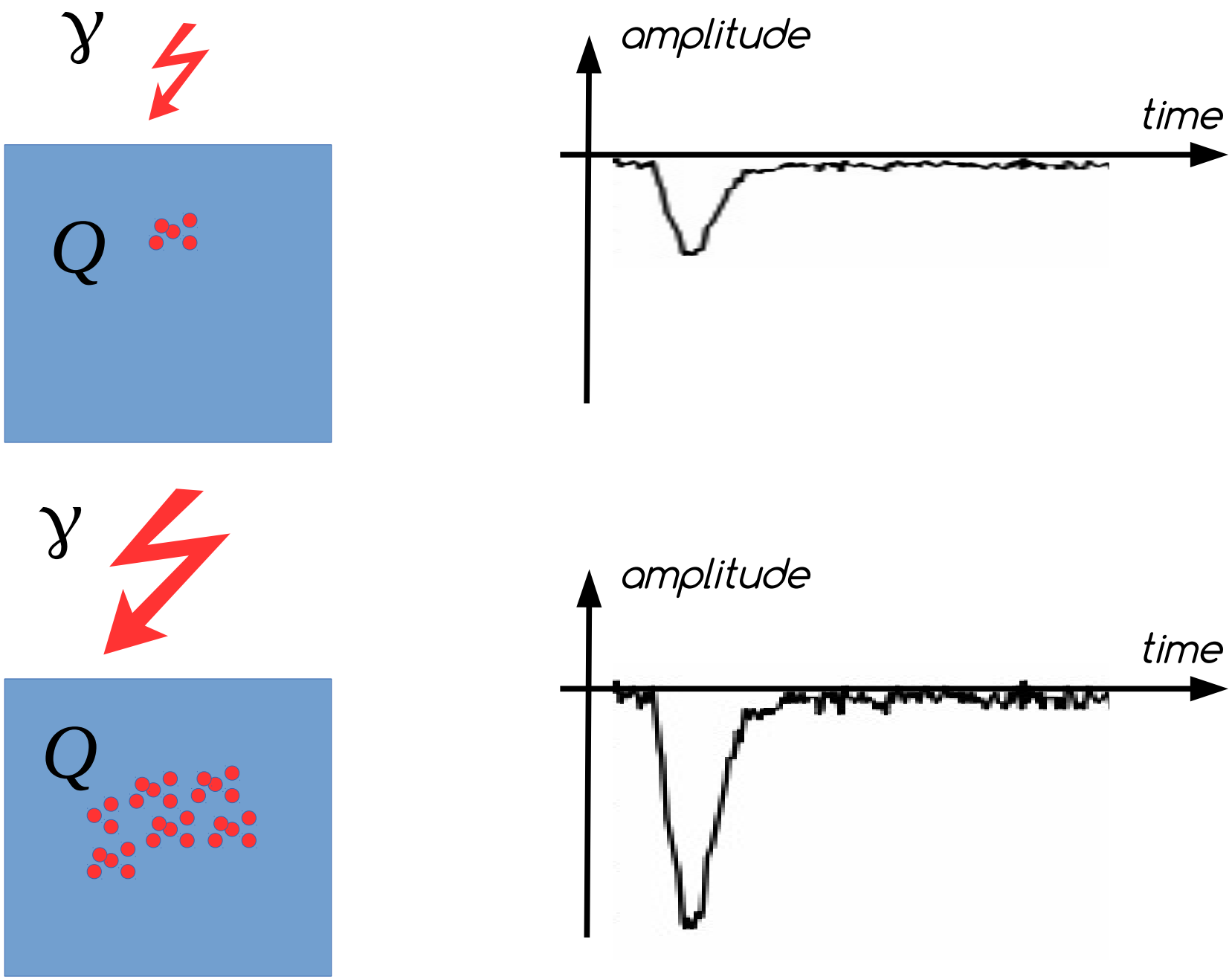
Charge is proportional to energy



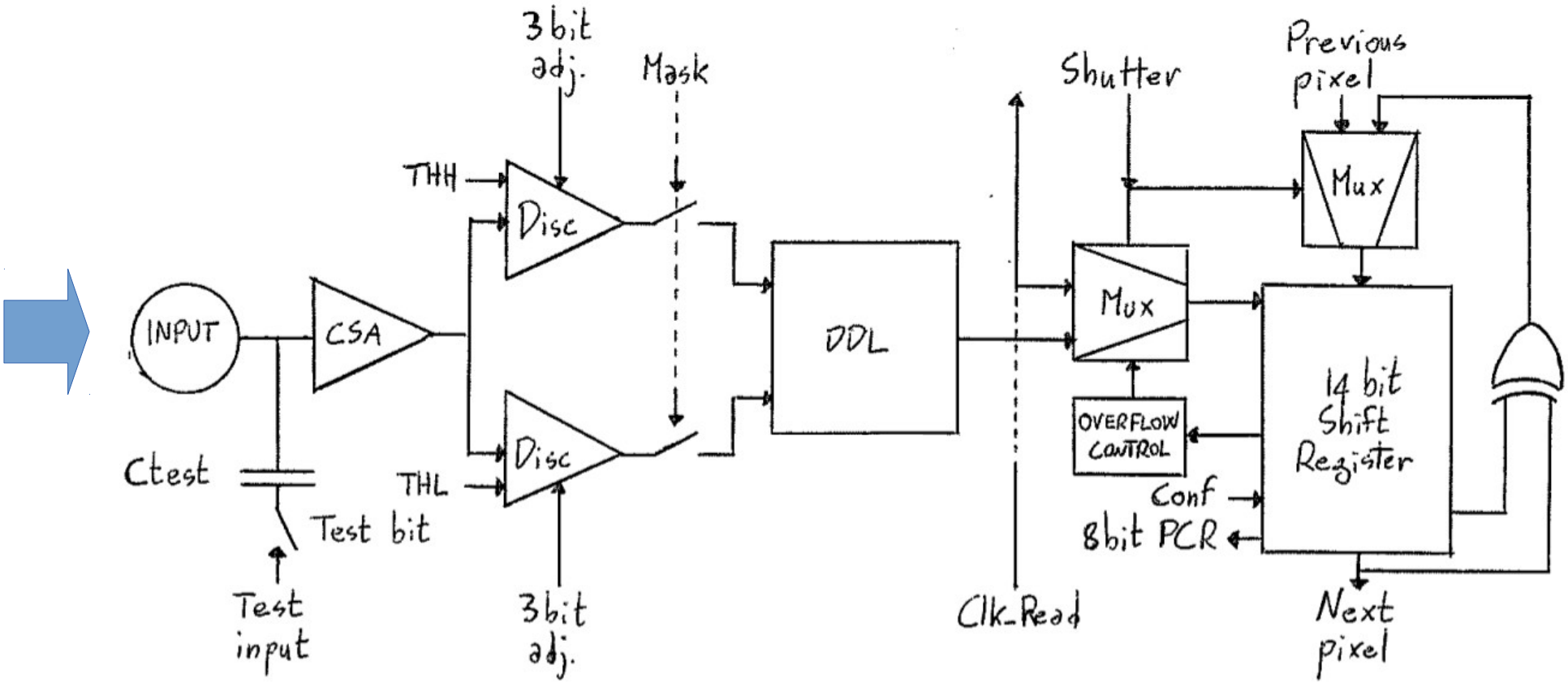
Charge is proportional to energy



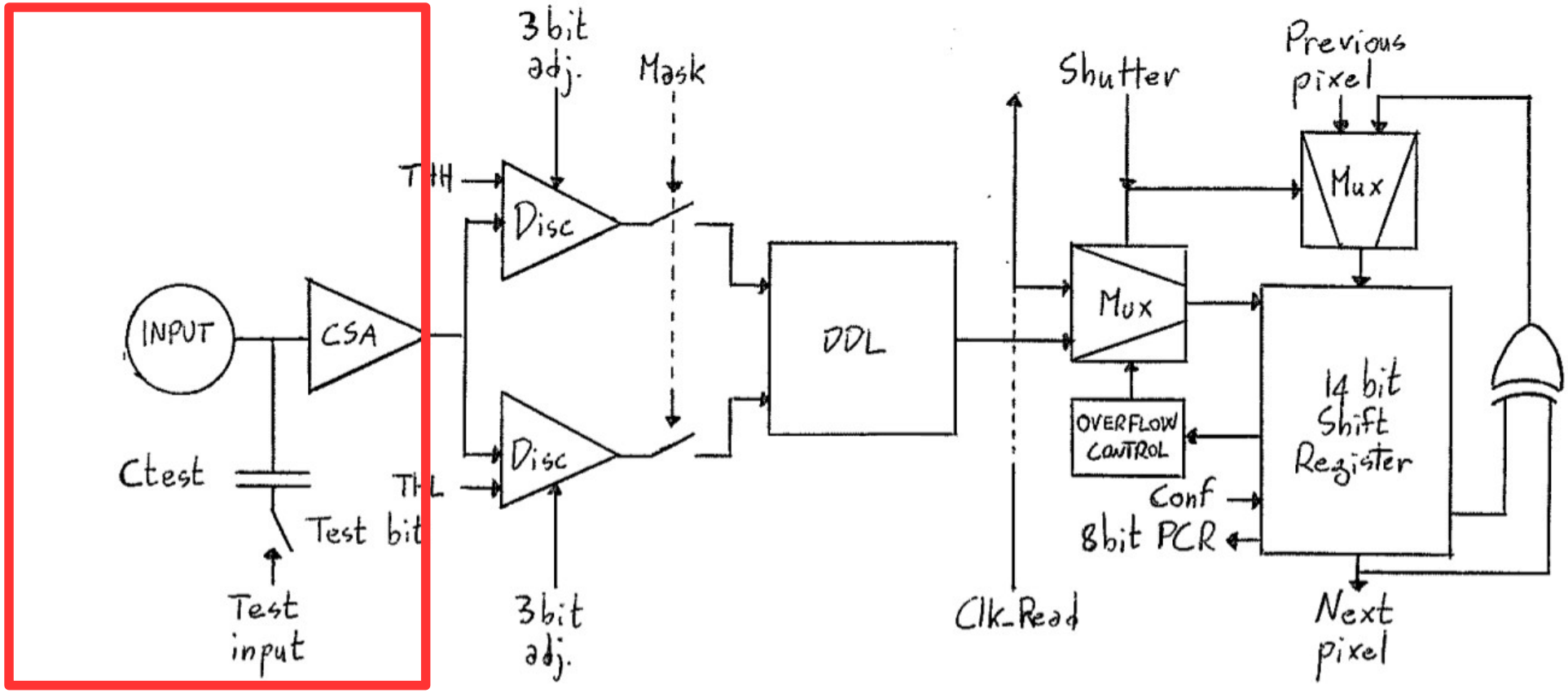
Charge is proportional to energy



Energy selective photon counting

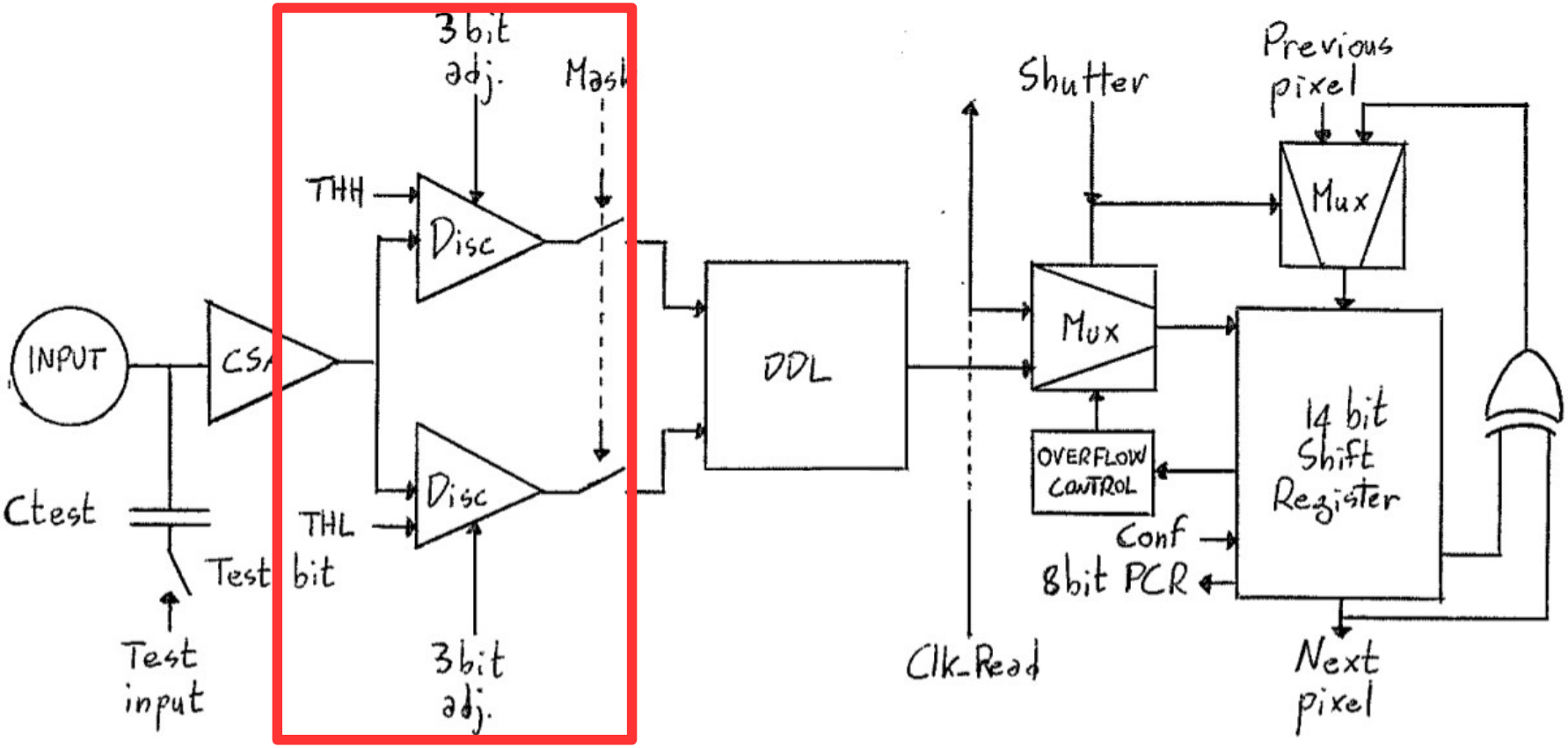


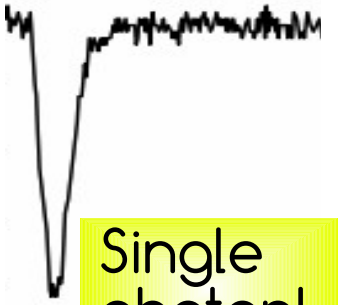
Energy selective photon counting



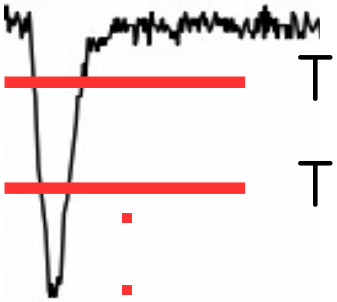
Single photon!

Energy selective photon counting





Single photon!

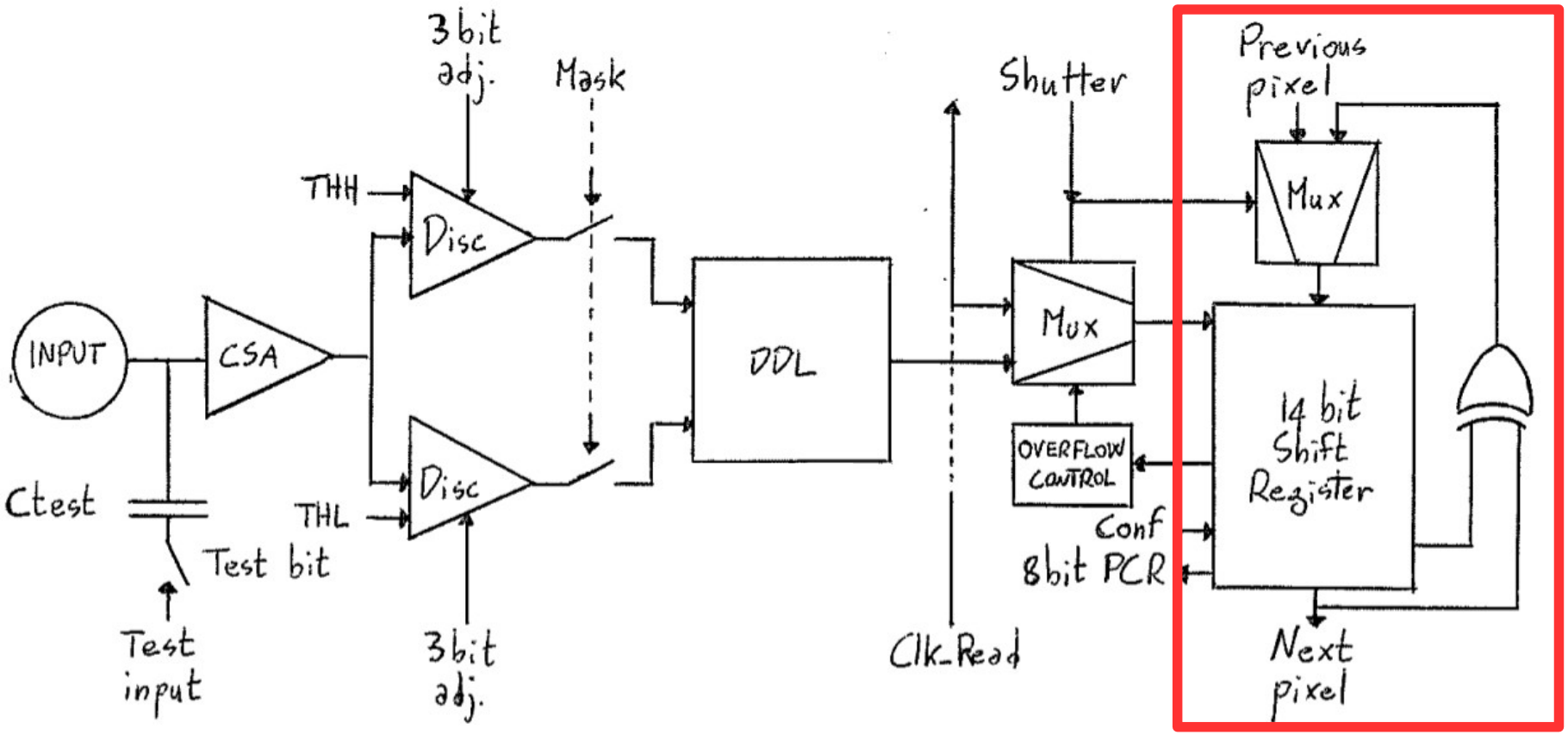


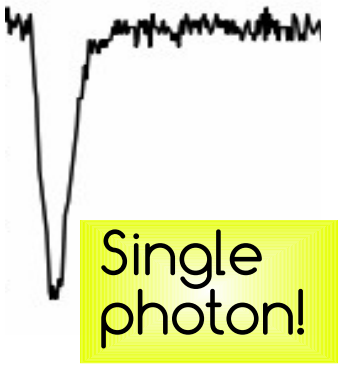
Threshold 1

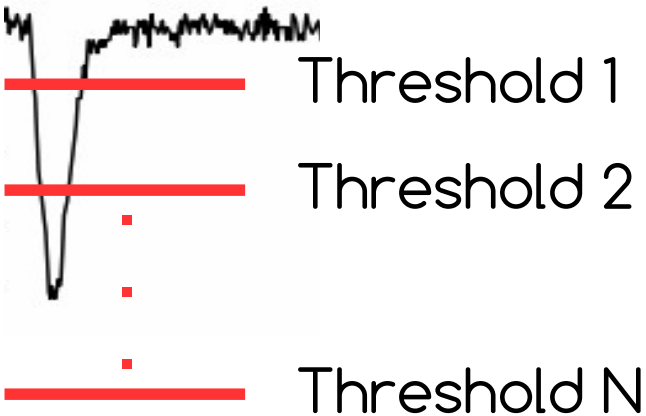
Threshold 2

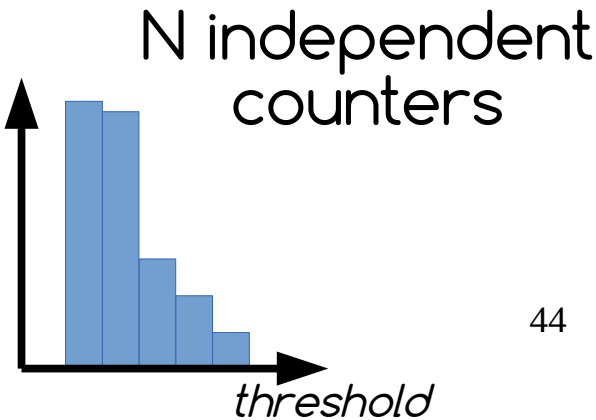
Threshold N

Energy selective photon counting

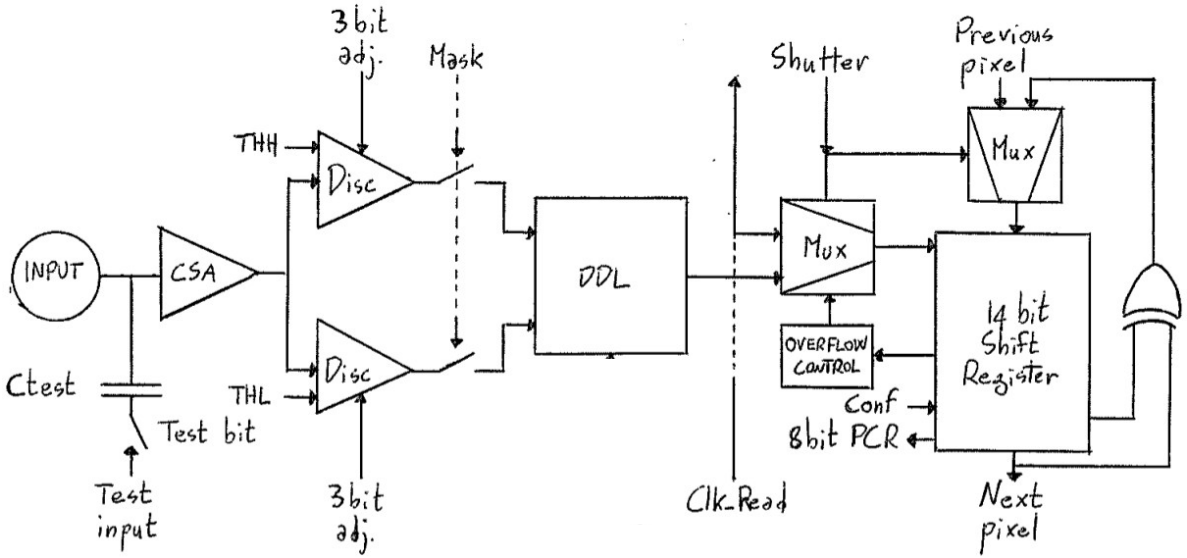




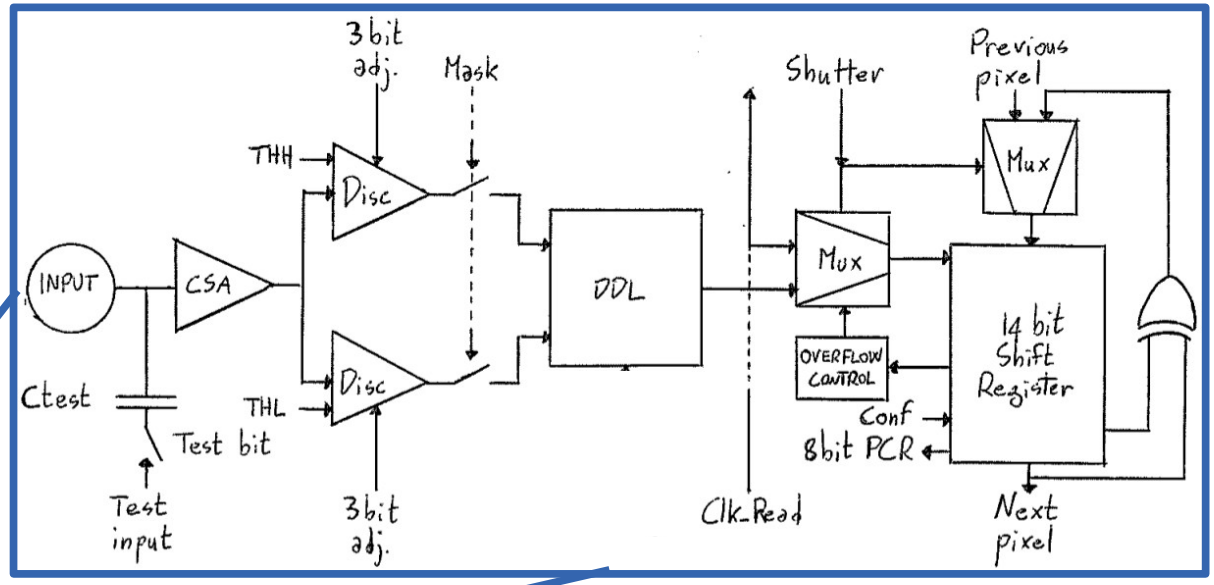


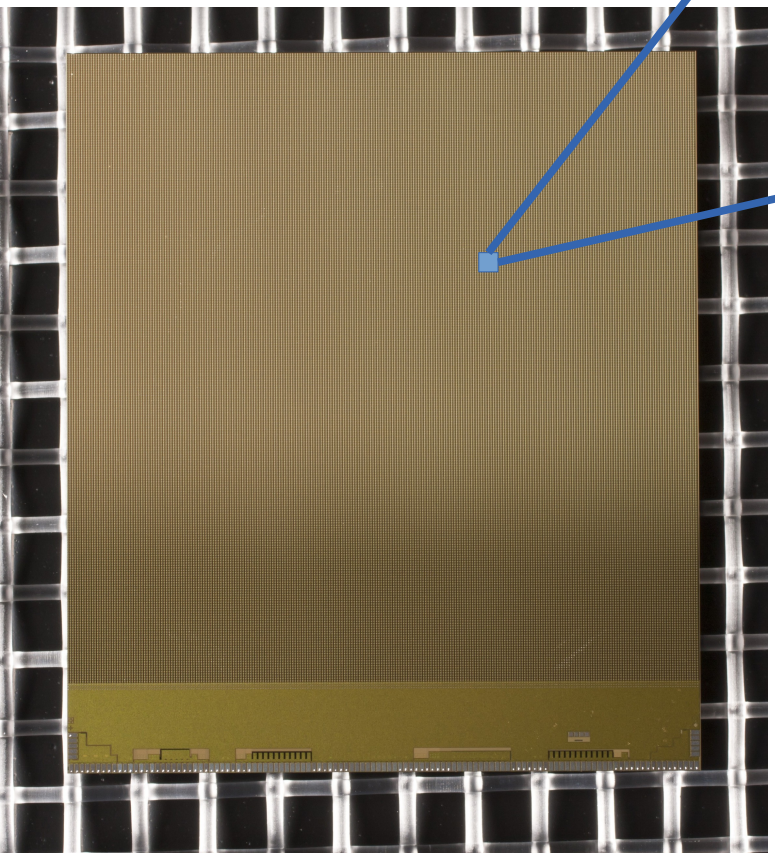


Spectroscopic pixel readout



Spectroscopic pixel readout

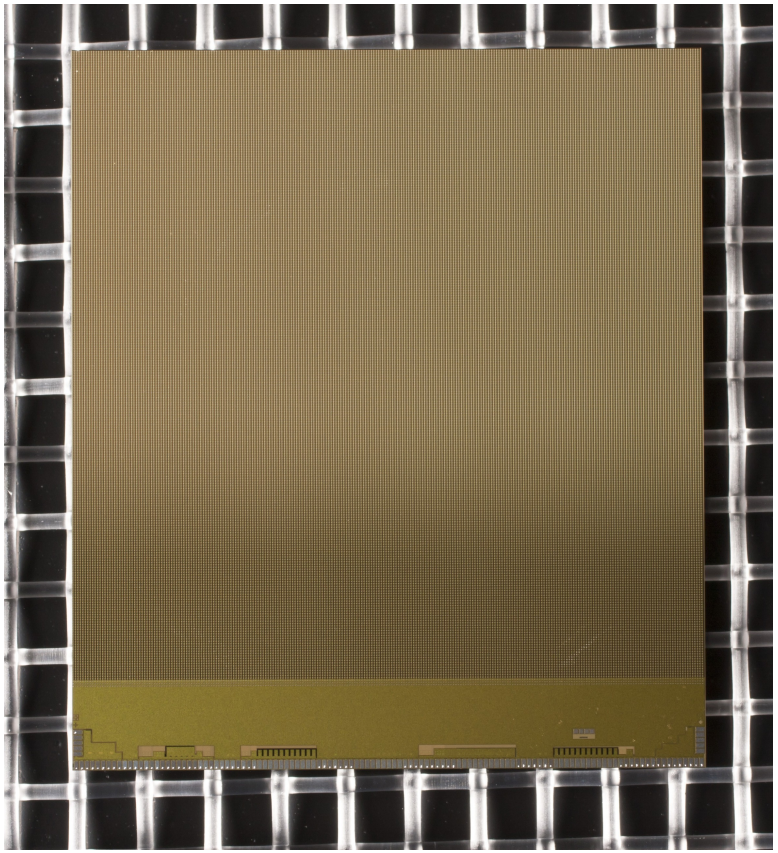




CMOS technology:

- Low power
- Low noise

An example: the Medipix2 chip



- 250 nm CMOS technology
- Pixel pitch = 55 um
- 256 x 256 = 65k (active) pixels
- "Electronic noise free"
- High dynamic range (depth of the photon counter)
- 3-side tilable → larger area
- 2 simultaneous thresholds, 1 counter

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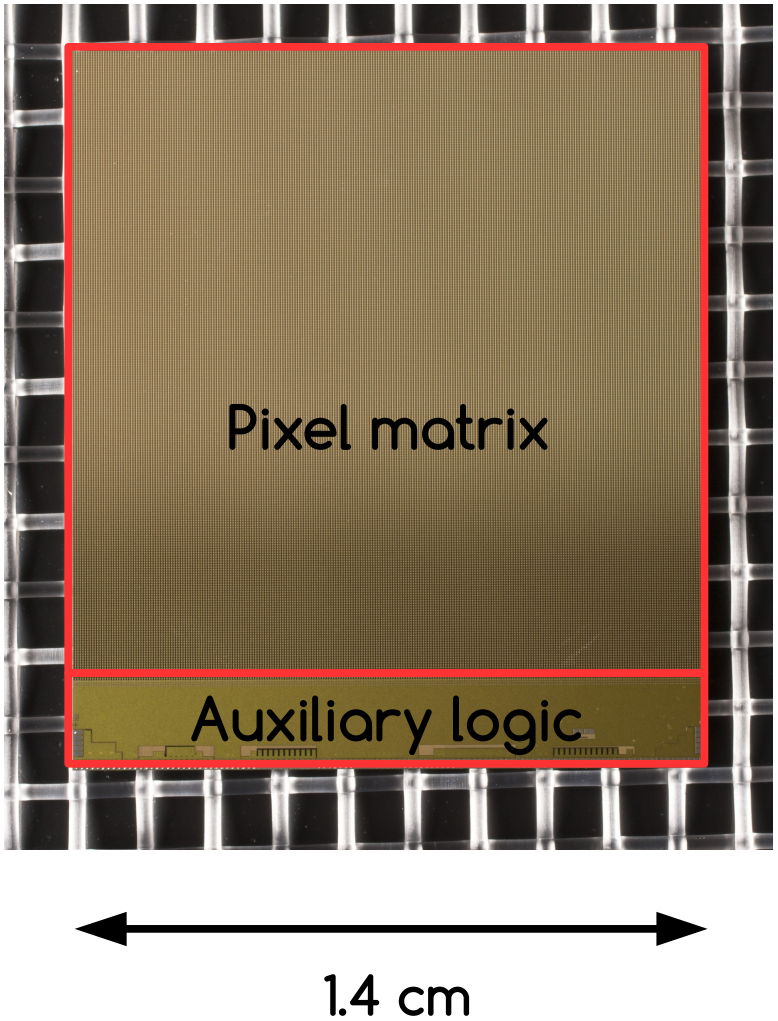

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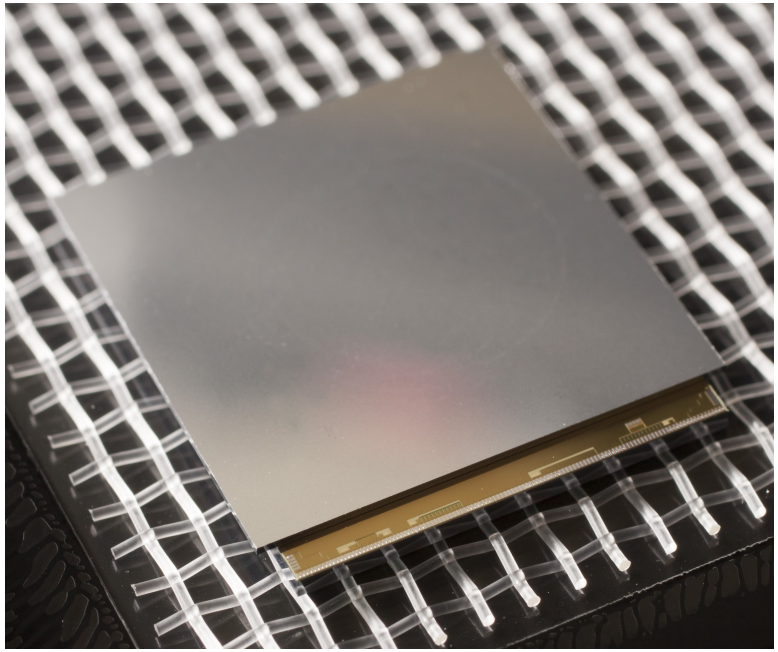
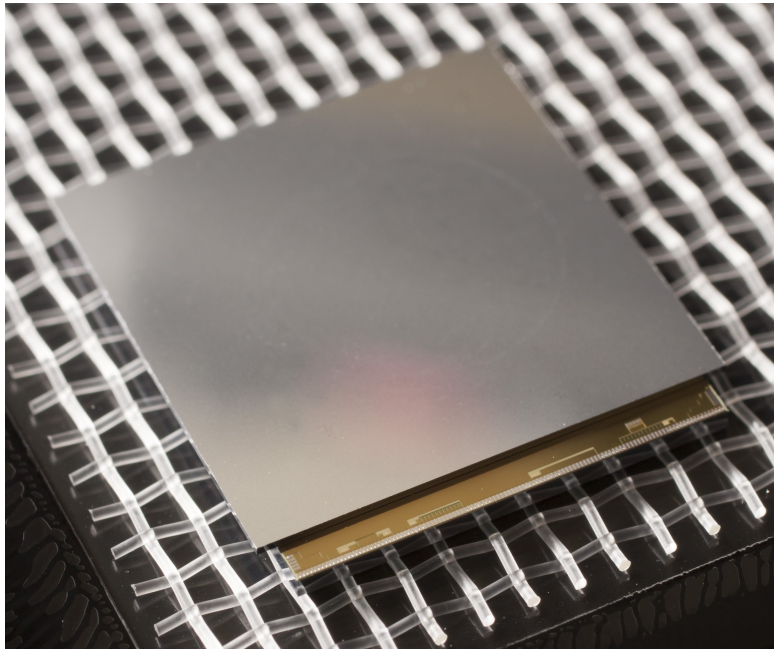
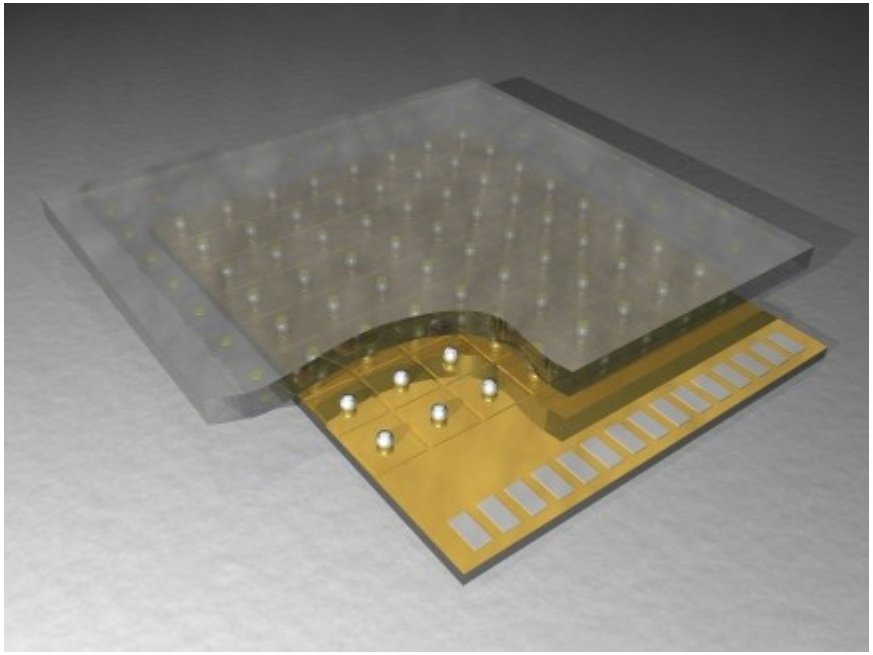
Hybrid detectors

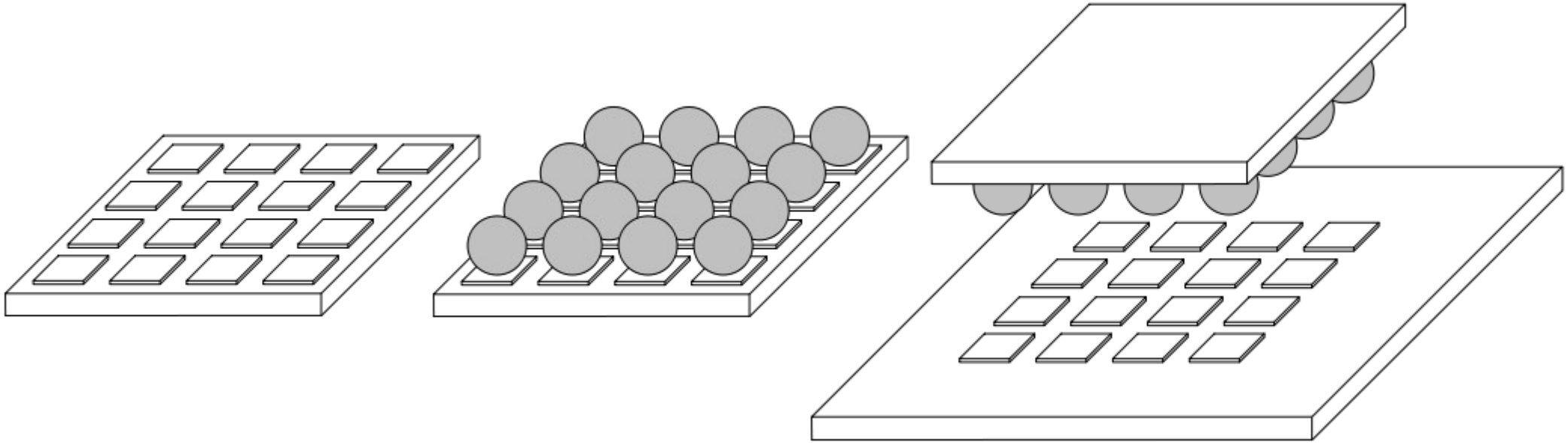


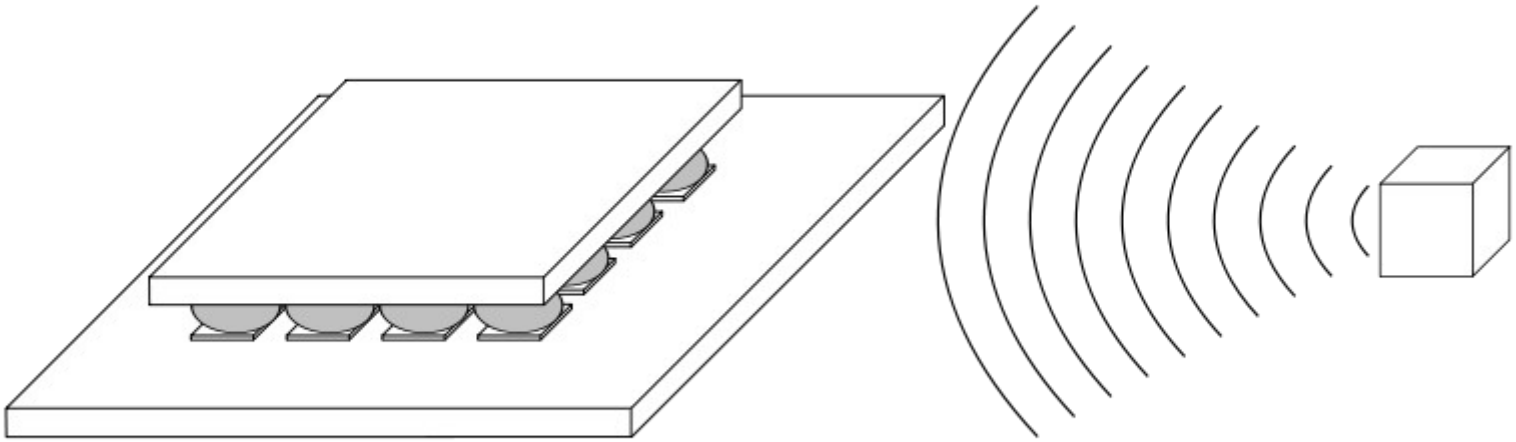
Hybrid detectors



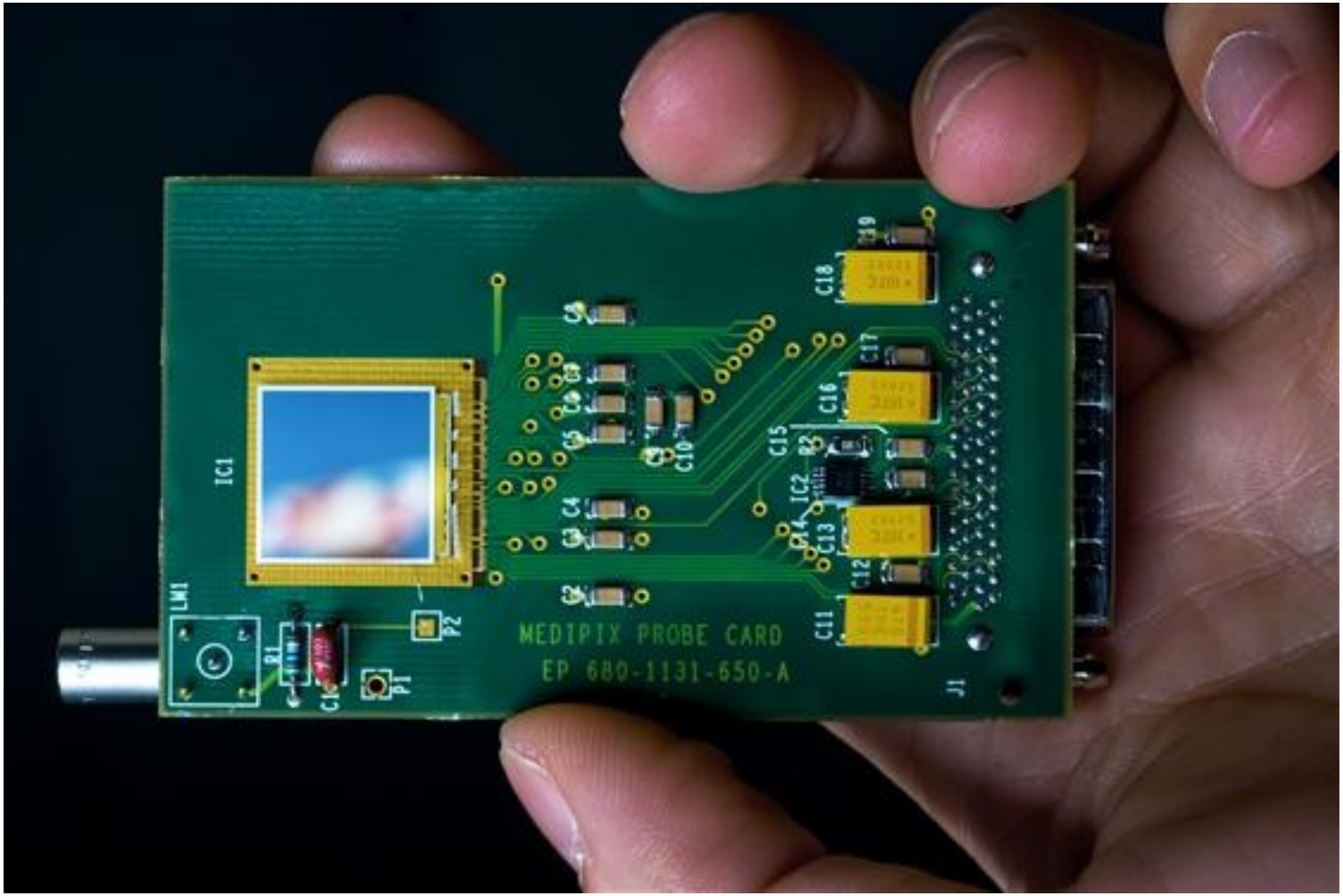


Flip chip bump bonding



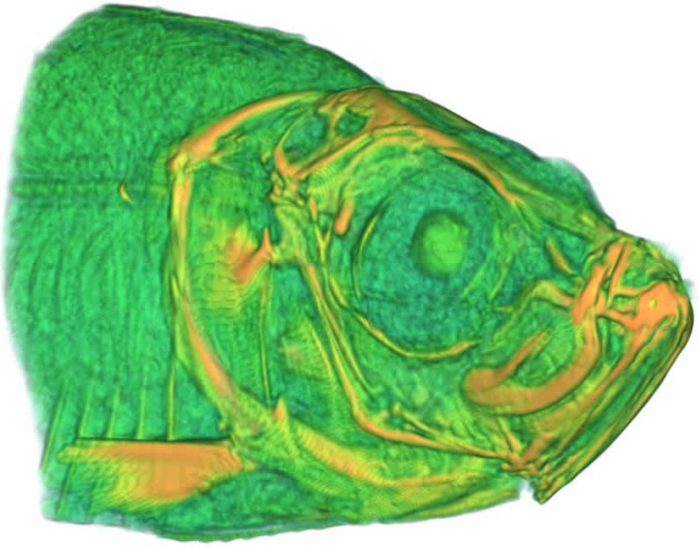


A Medipix2 assembly

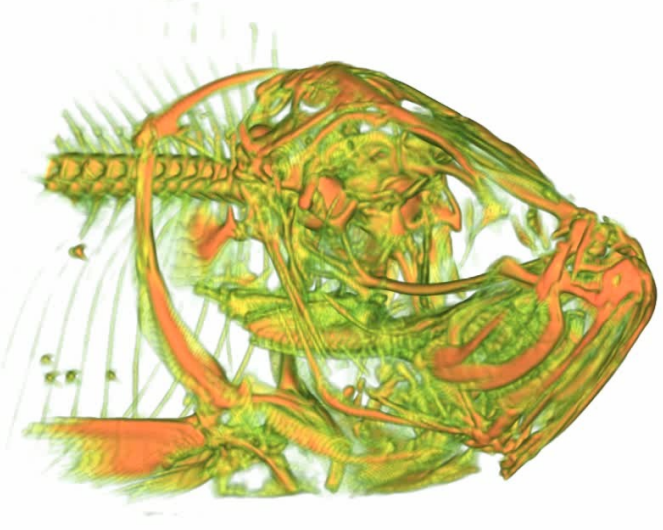


Typical sensors for X-ray applications:
300 um silicon

An example of CT using a Medipix-based detector



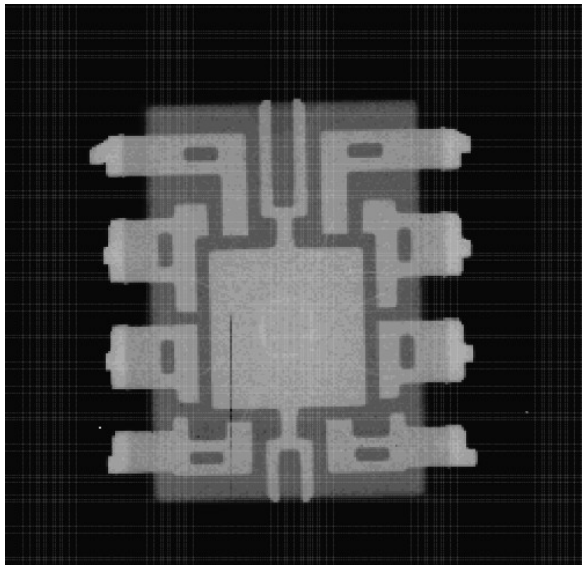
2 cm



WARNING!

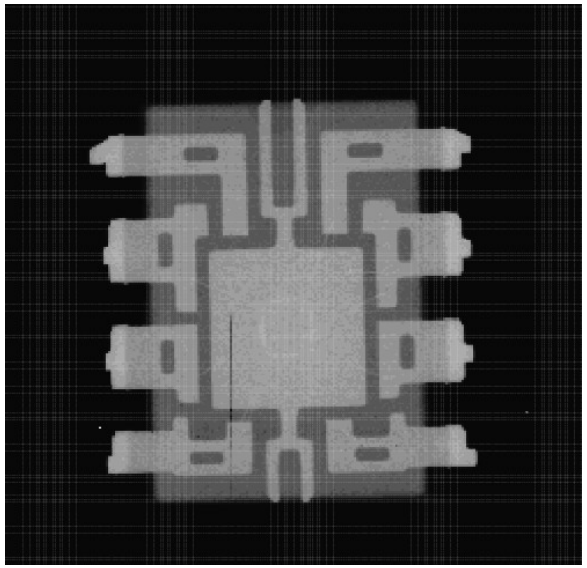
This is still a grayscale!

Imaging at multiple thresholds

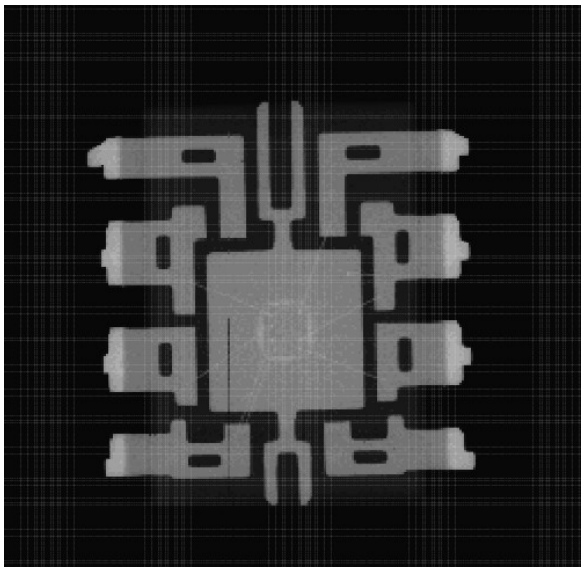


threshold
5 keV

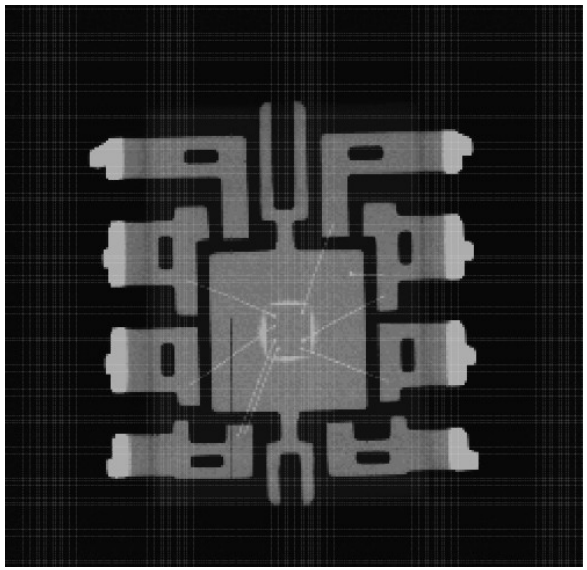
Imaging at multiple thresholds



threshold
5 keV

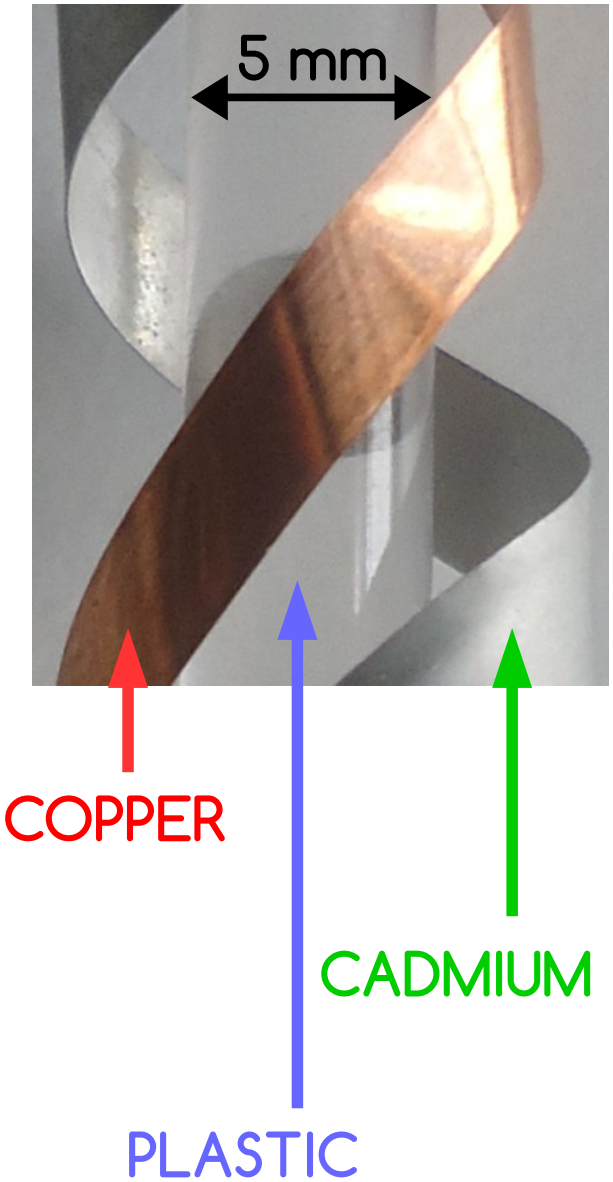


threshold
10 keV

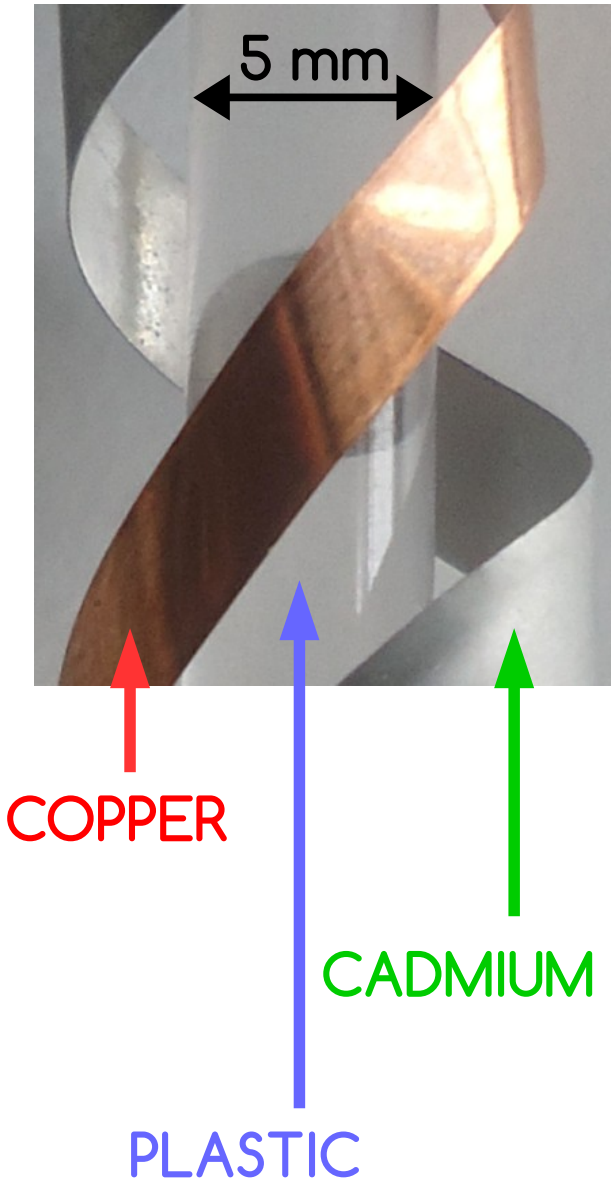


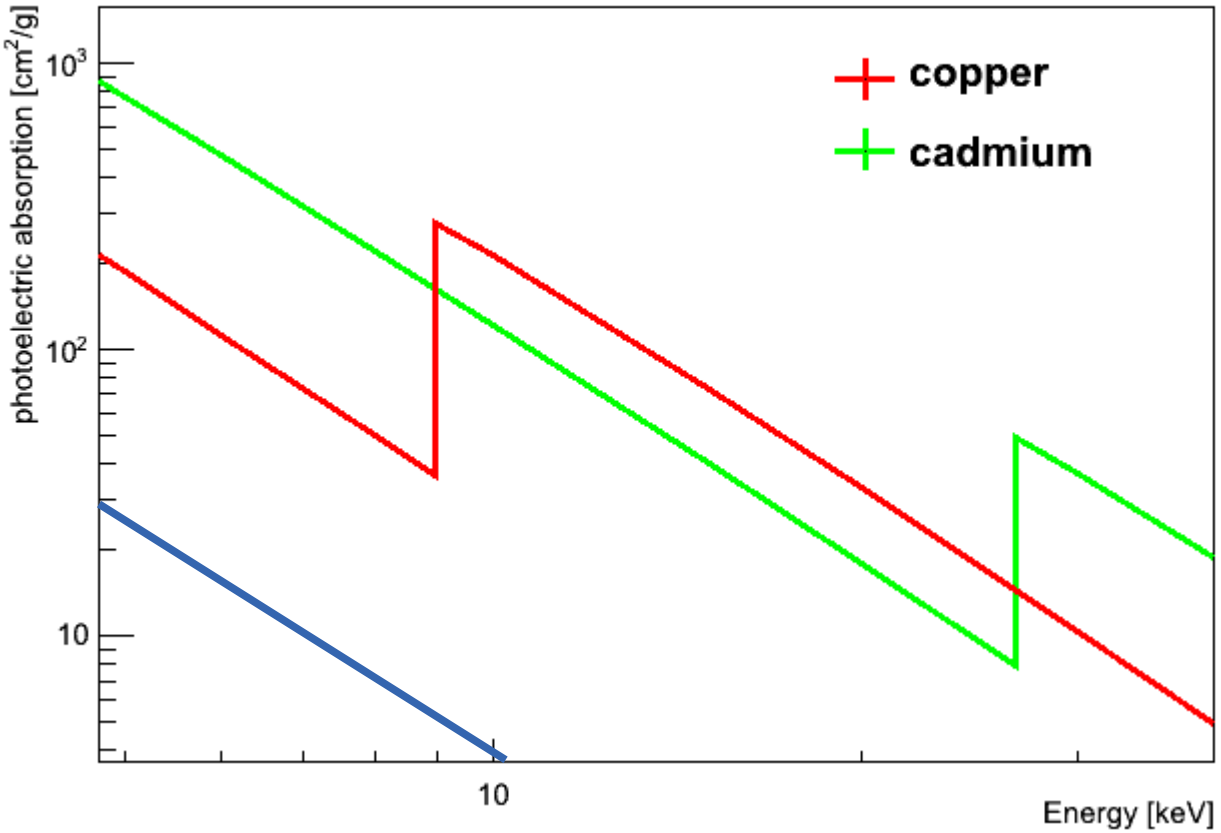
threshold
27 keV

A color (i.e. material resolved) CT

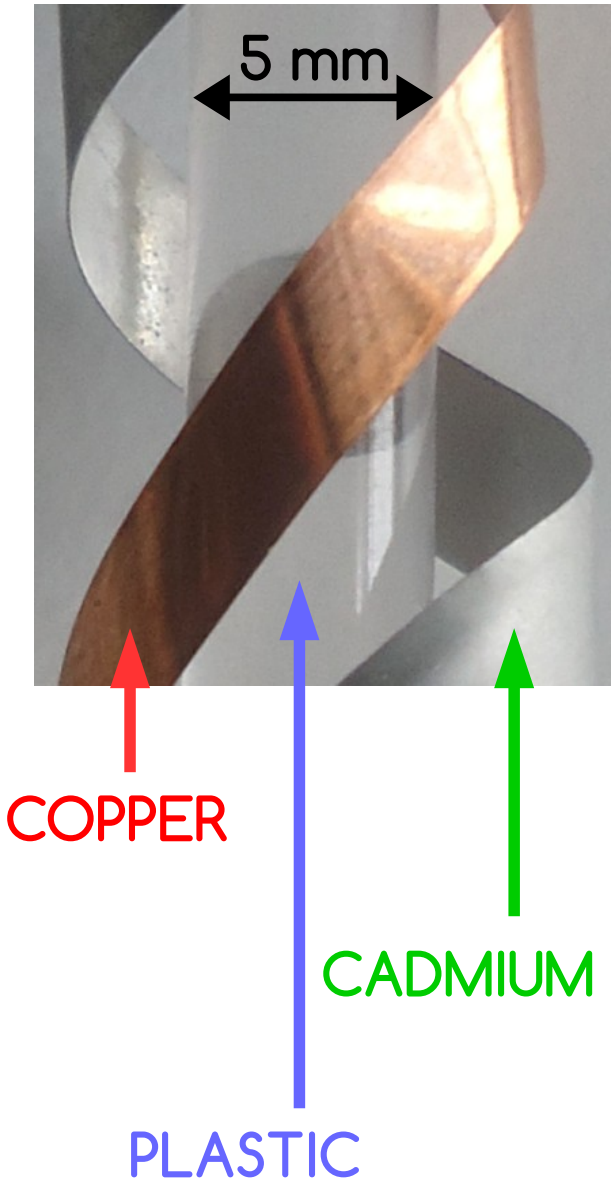


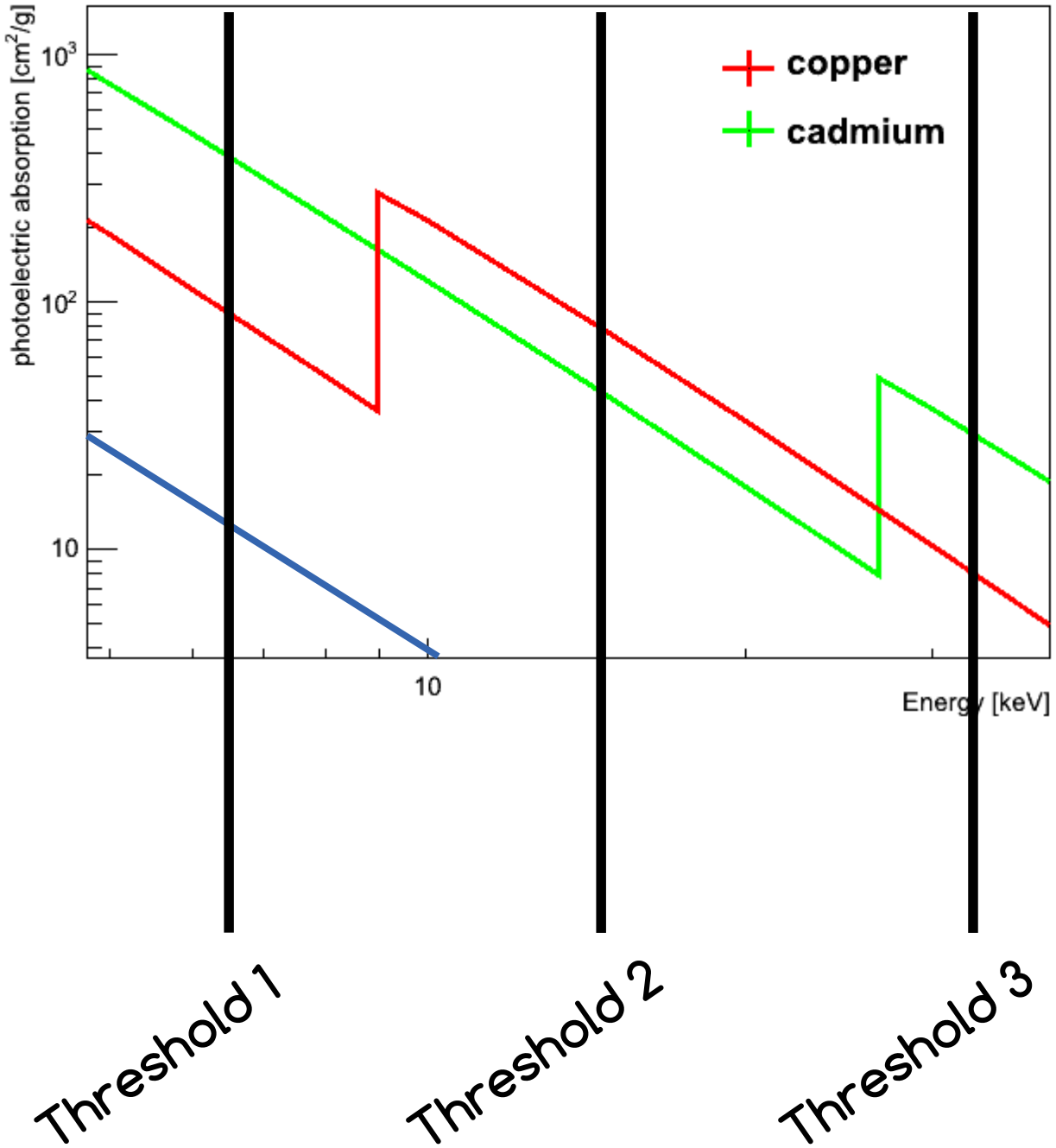
A color (i.e. material resolved) CT



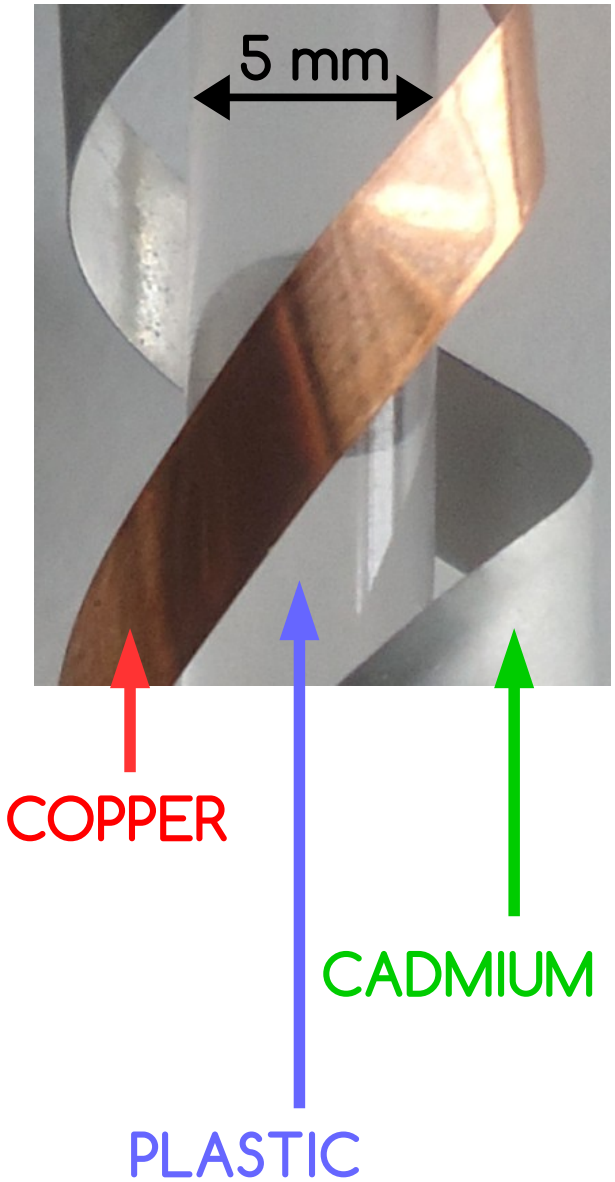


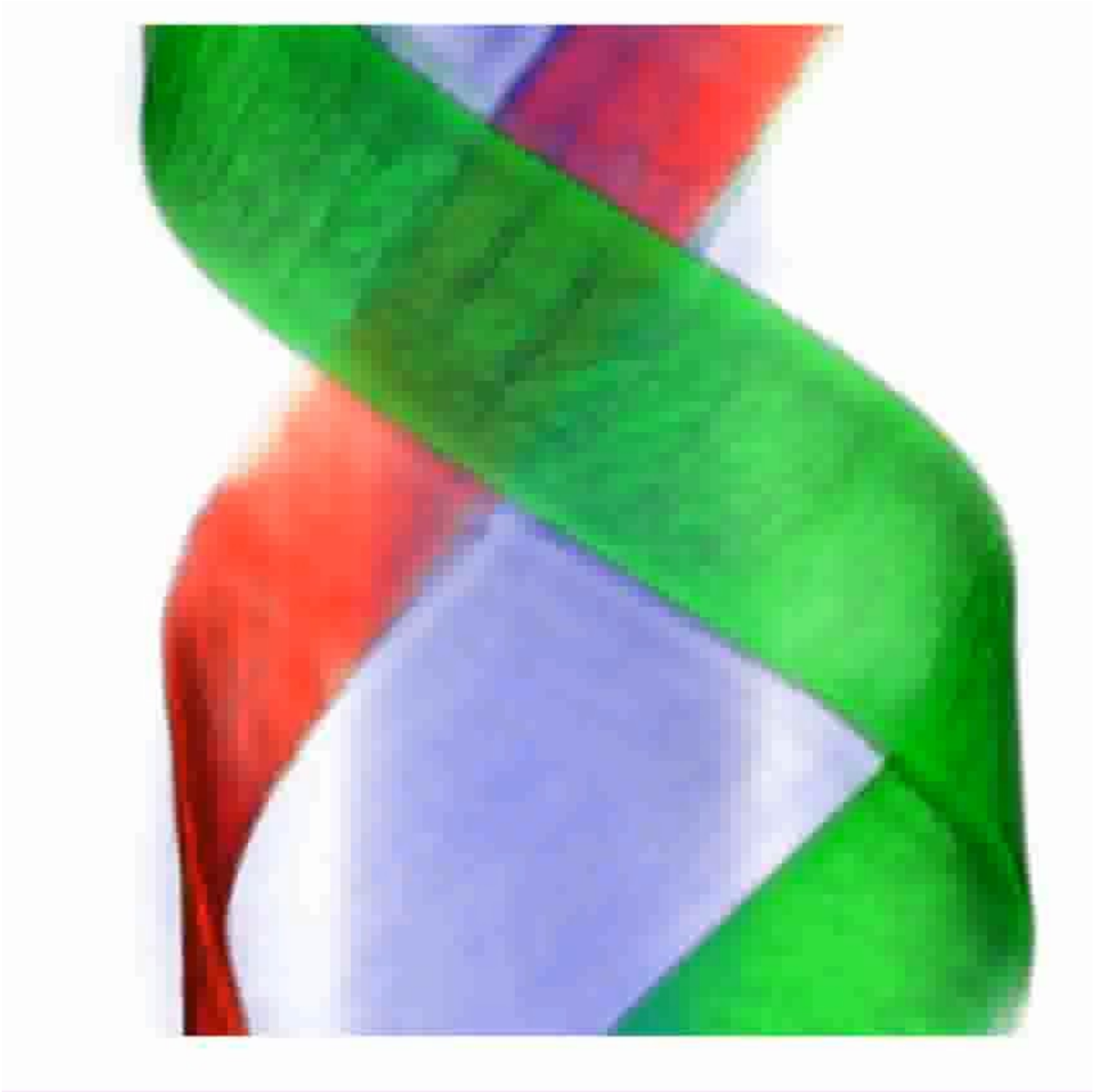
A color (i.e. material resolved) CT





A color (i.e. material resolved) CT





All very nice, but can you see the limitations?

How to really solve CT?

$$N_{l,\theta,t} = \int_{t}^{+\infty} \ldots R(E, E') \ldots e^{-\int_{l,\theta} \sum_{m}^{M} \alpha_m \mu_m(s, E)\, ds}$$

1 - the threshold trick

2 - the detector response

3 – how do we invert the integral?

How to really solve CT?

$$N_{l,\theta,t} = \int_t^{+\infty} \ldots R(E, E') \ldots e^{-\int_{l,\theta} \sum_m^M \alpha_m \mu_m(s,E)\, ds}$$

1 - the threshold trick

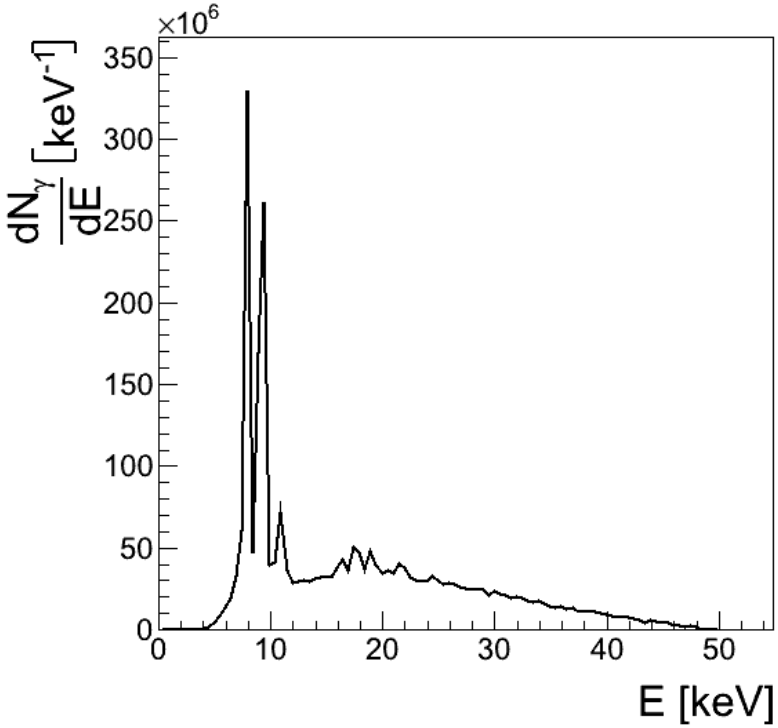
2 - the detector response

3 – how do we invert the integral?

The energy response function

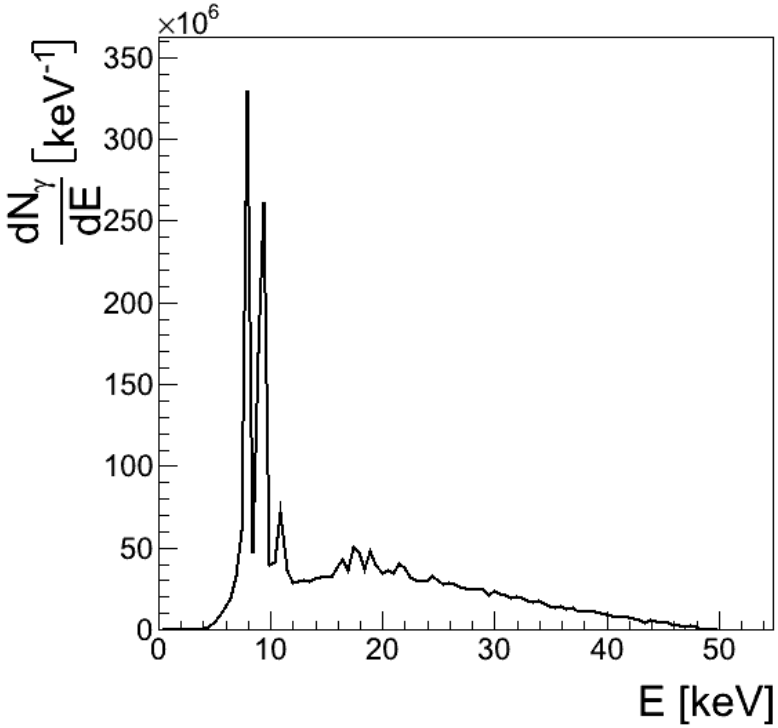
Medipix2-based silicon detector (300 um, hole collecting)

Spectral distortions due to detector effects

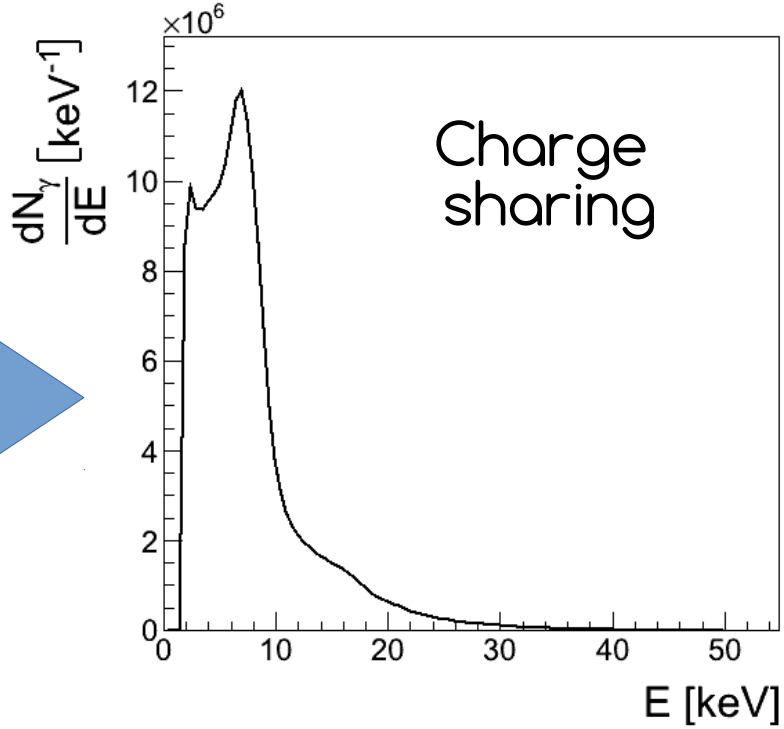


Incoming spectrum

Spectral distortions due to detector effects

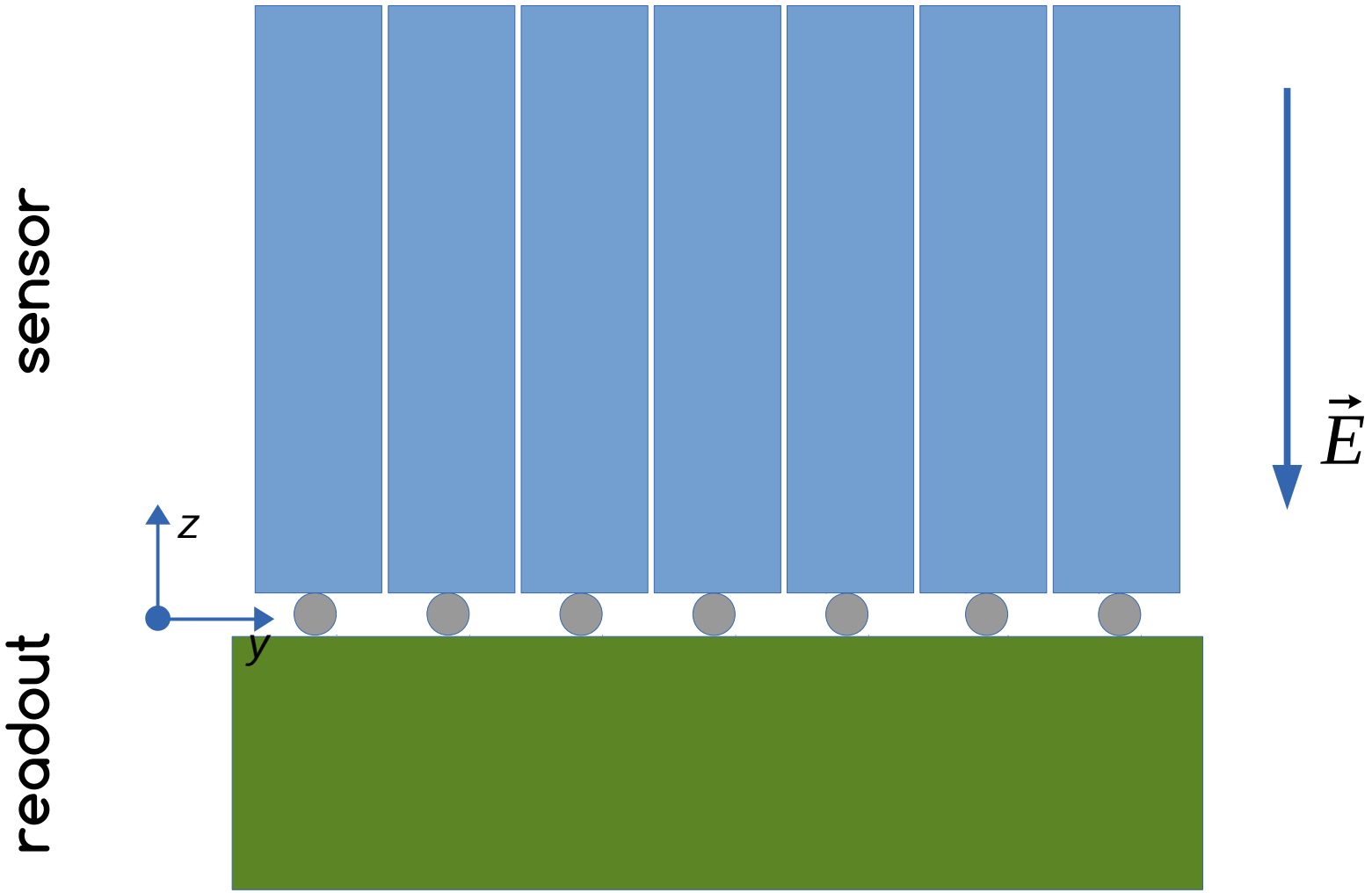


Incoming spectrum

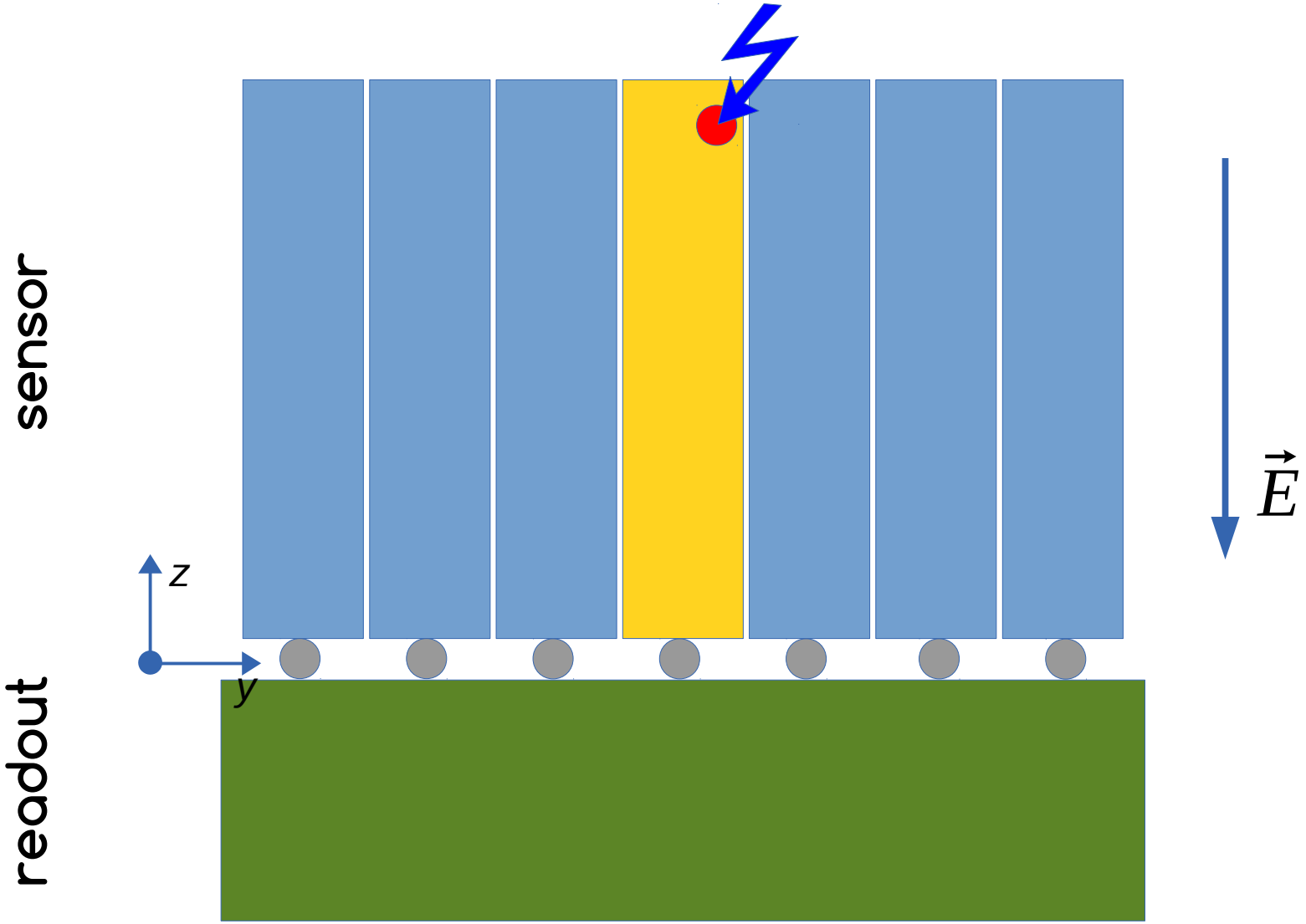


Detected spectrum

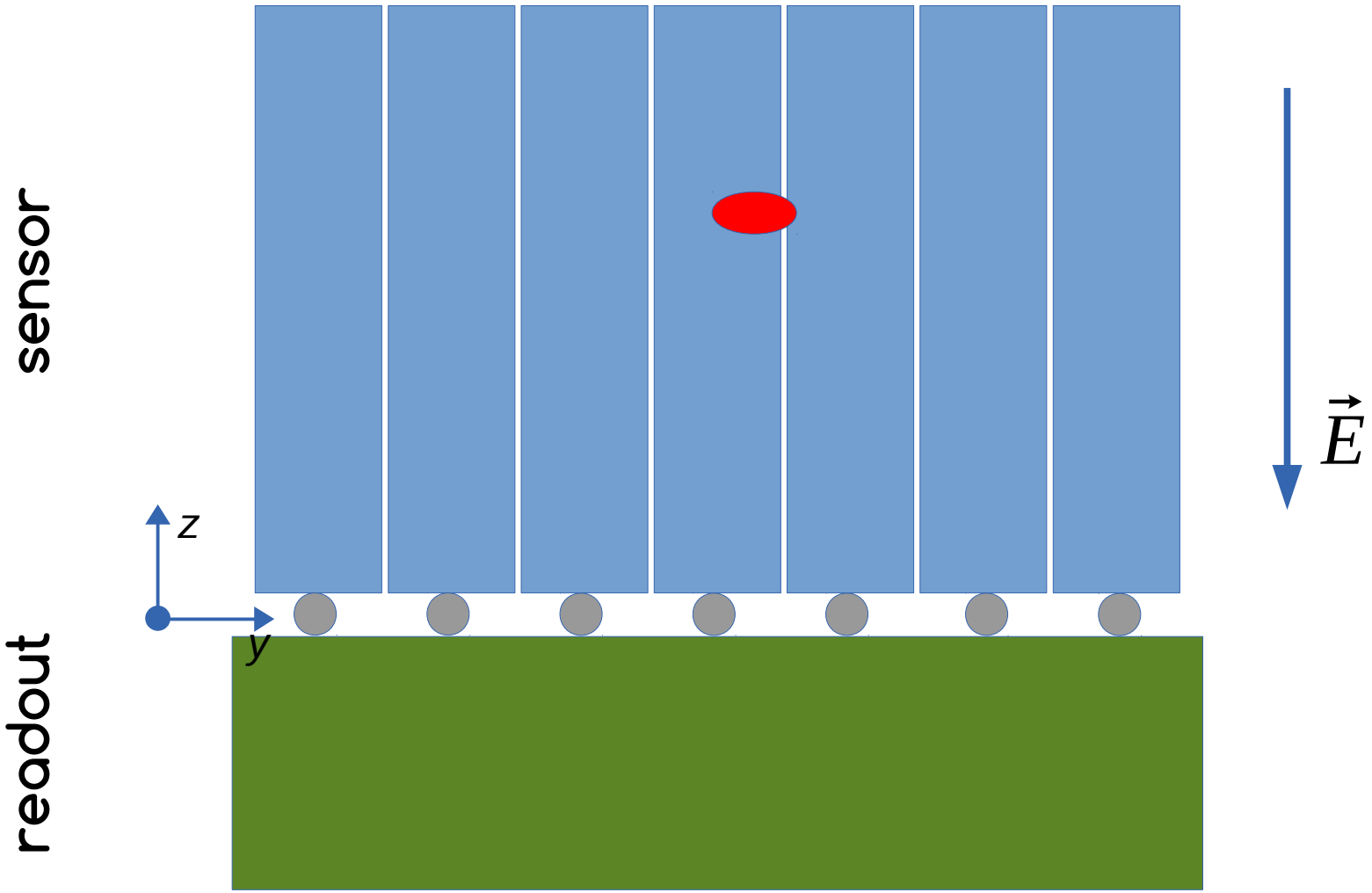
Charge sharing



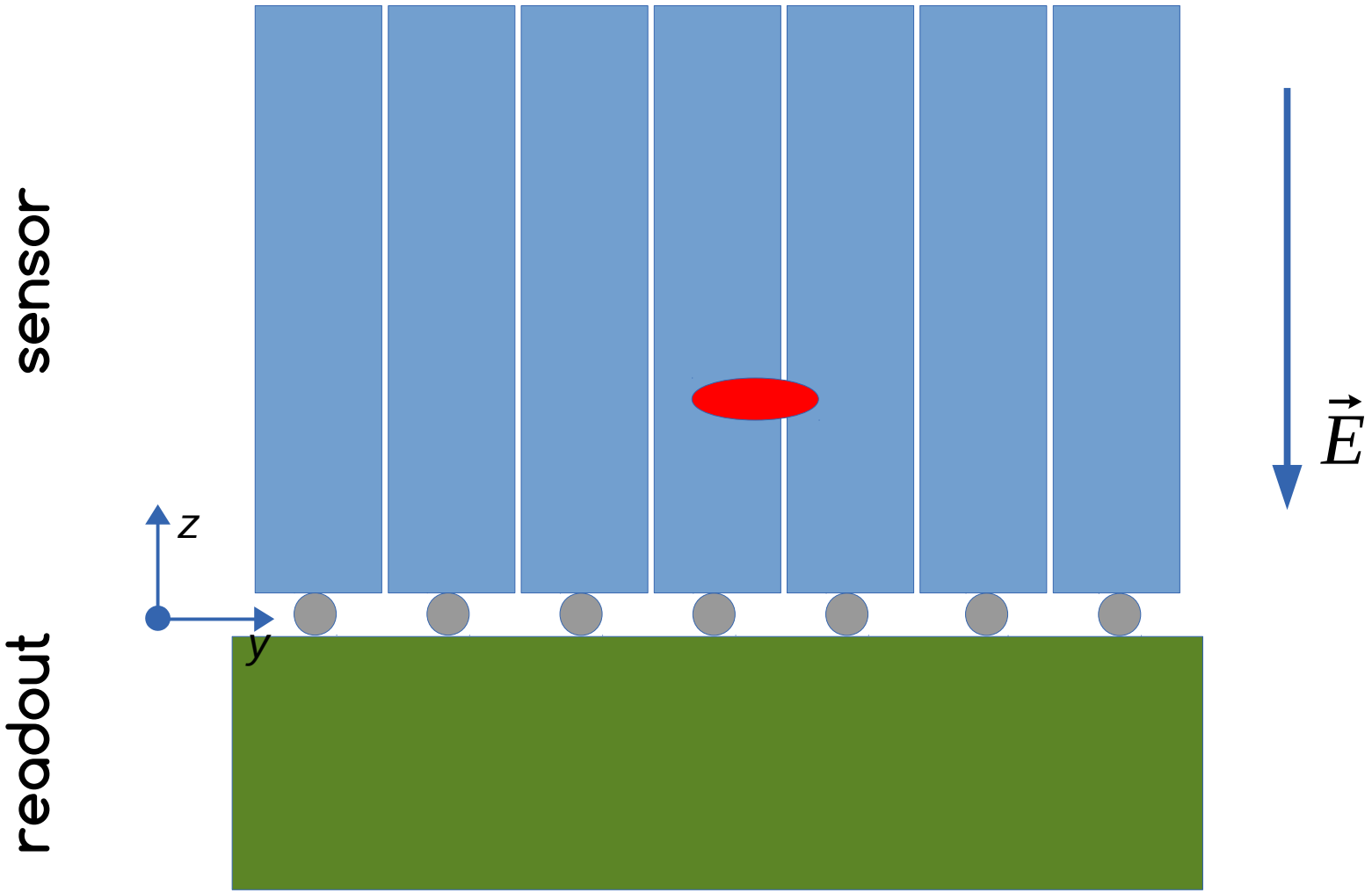
Charge sharing



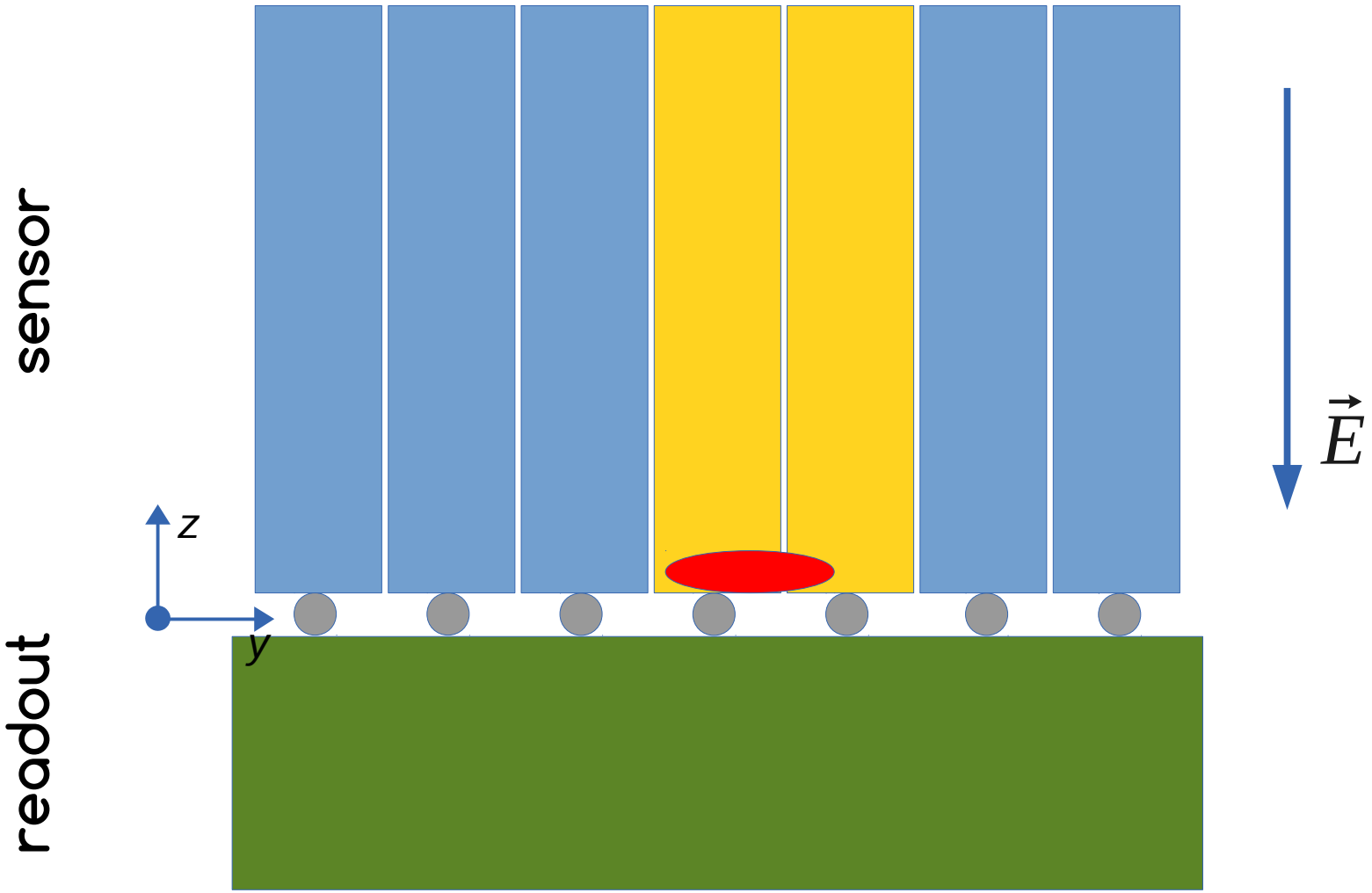
Charge sharing



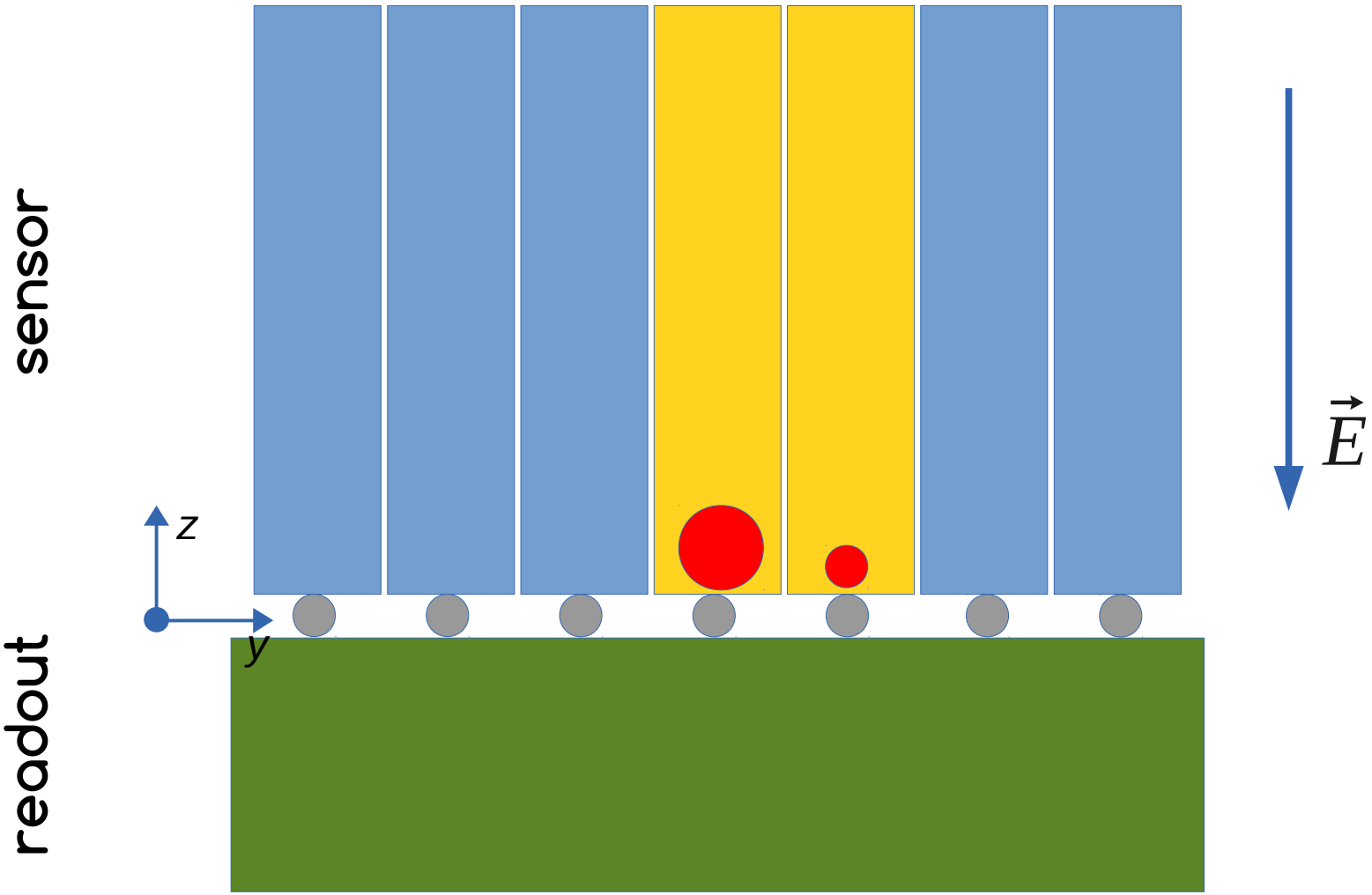
Charge sharing



Charge sharing

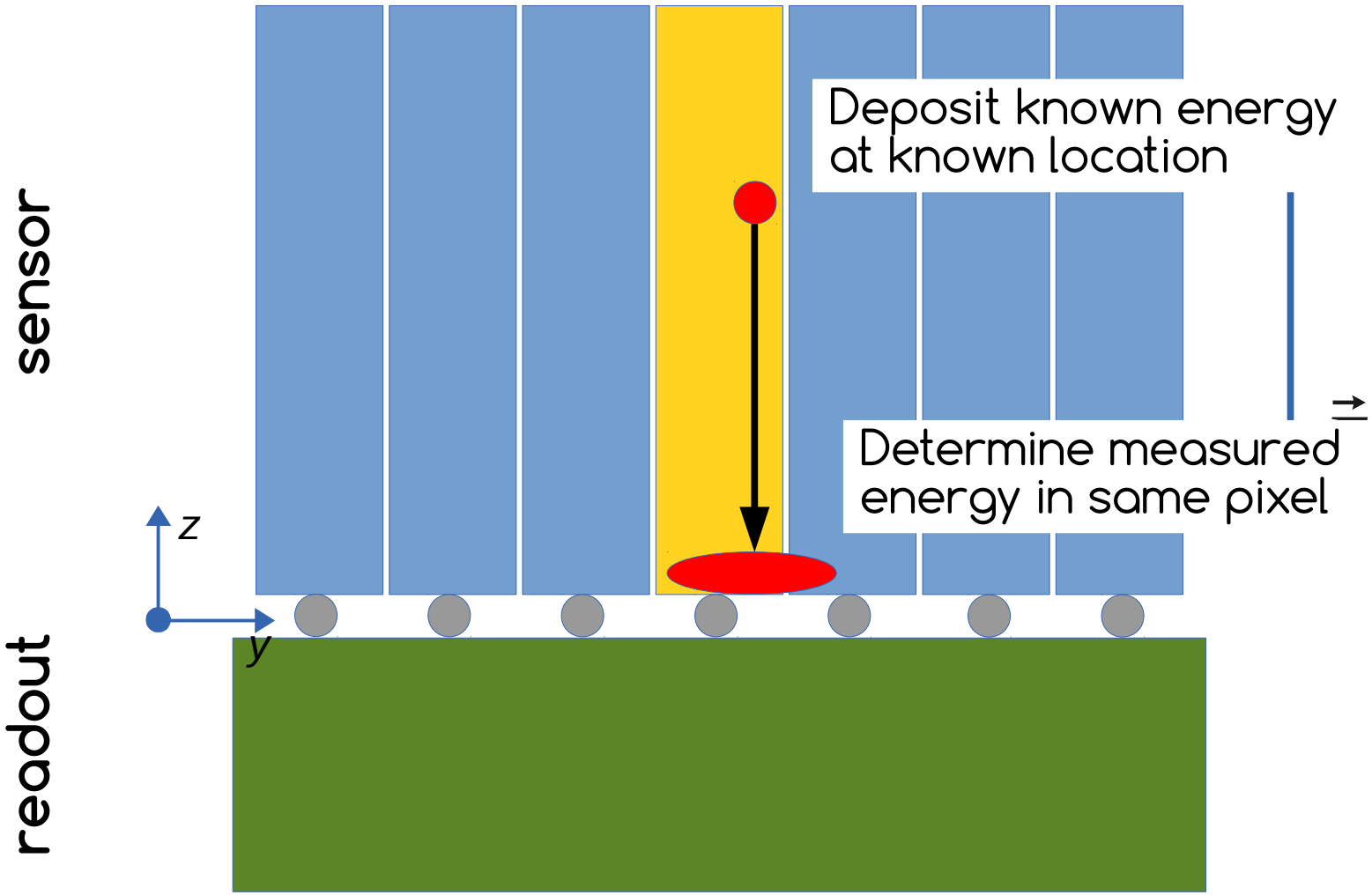


Charge sharing

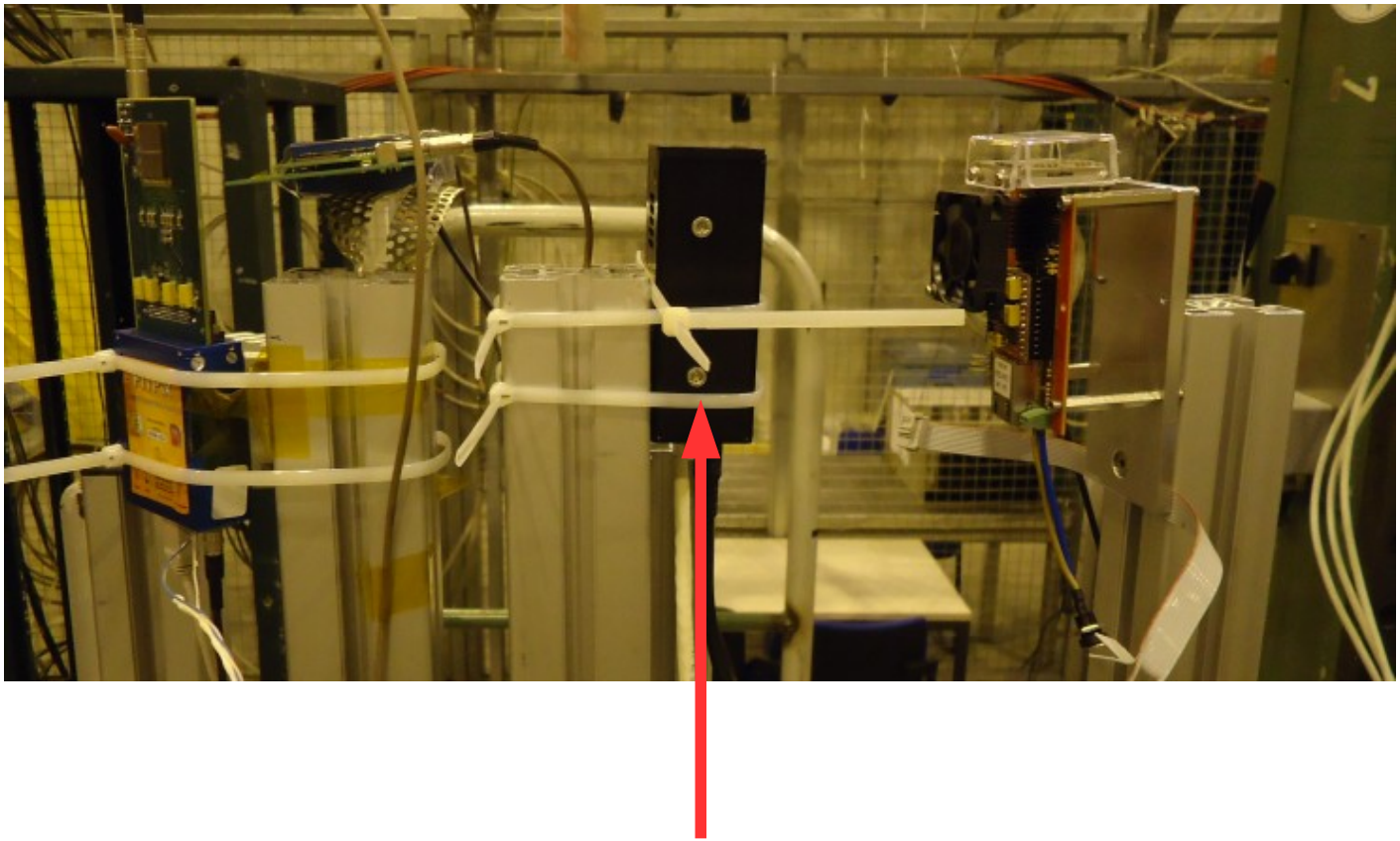


Need to study transport properties of the sensor!

Idea for an experiment

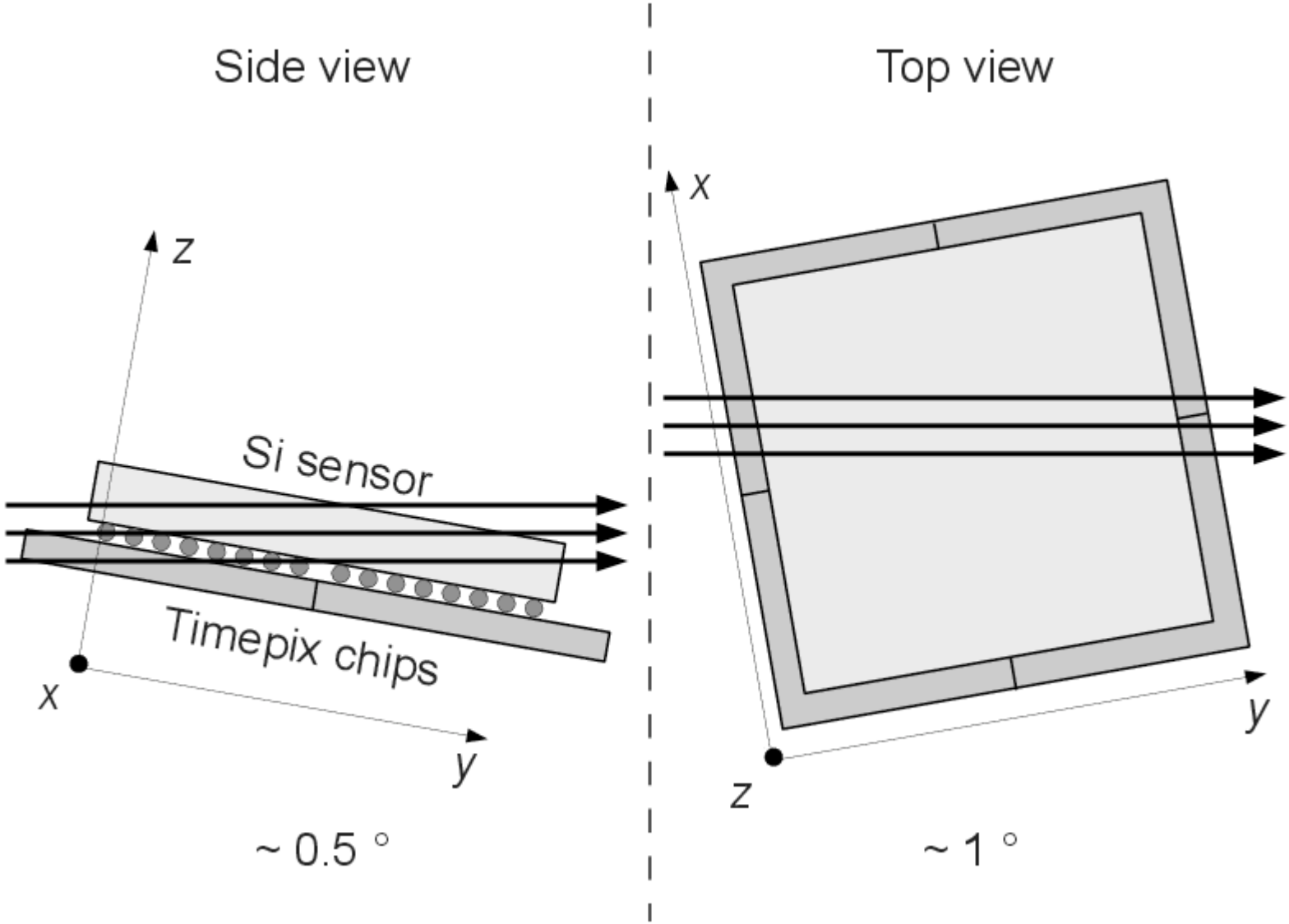


CERN test beam with 40 GeV pions

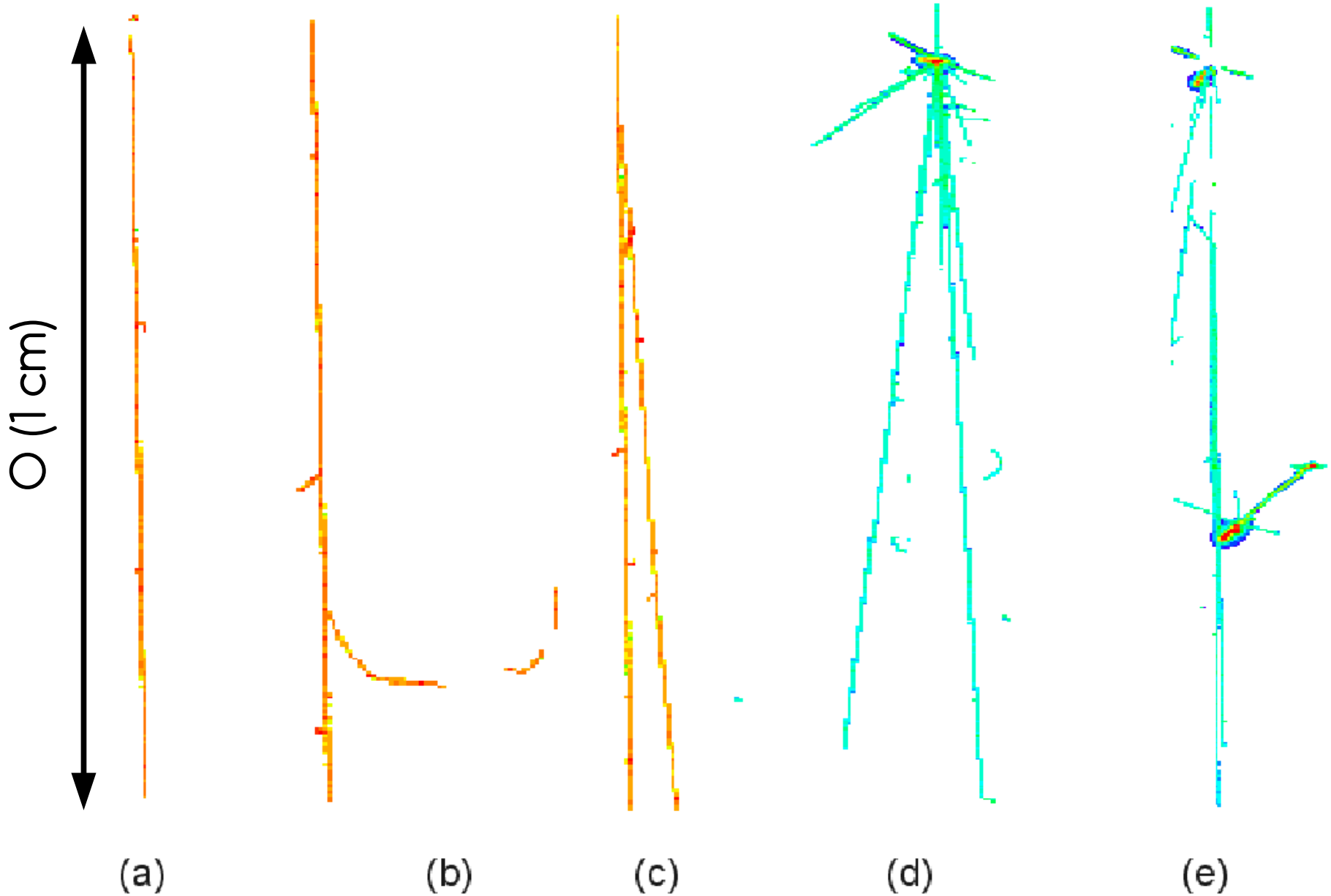


Timepix quad

Detector positioning in the beam

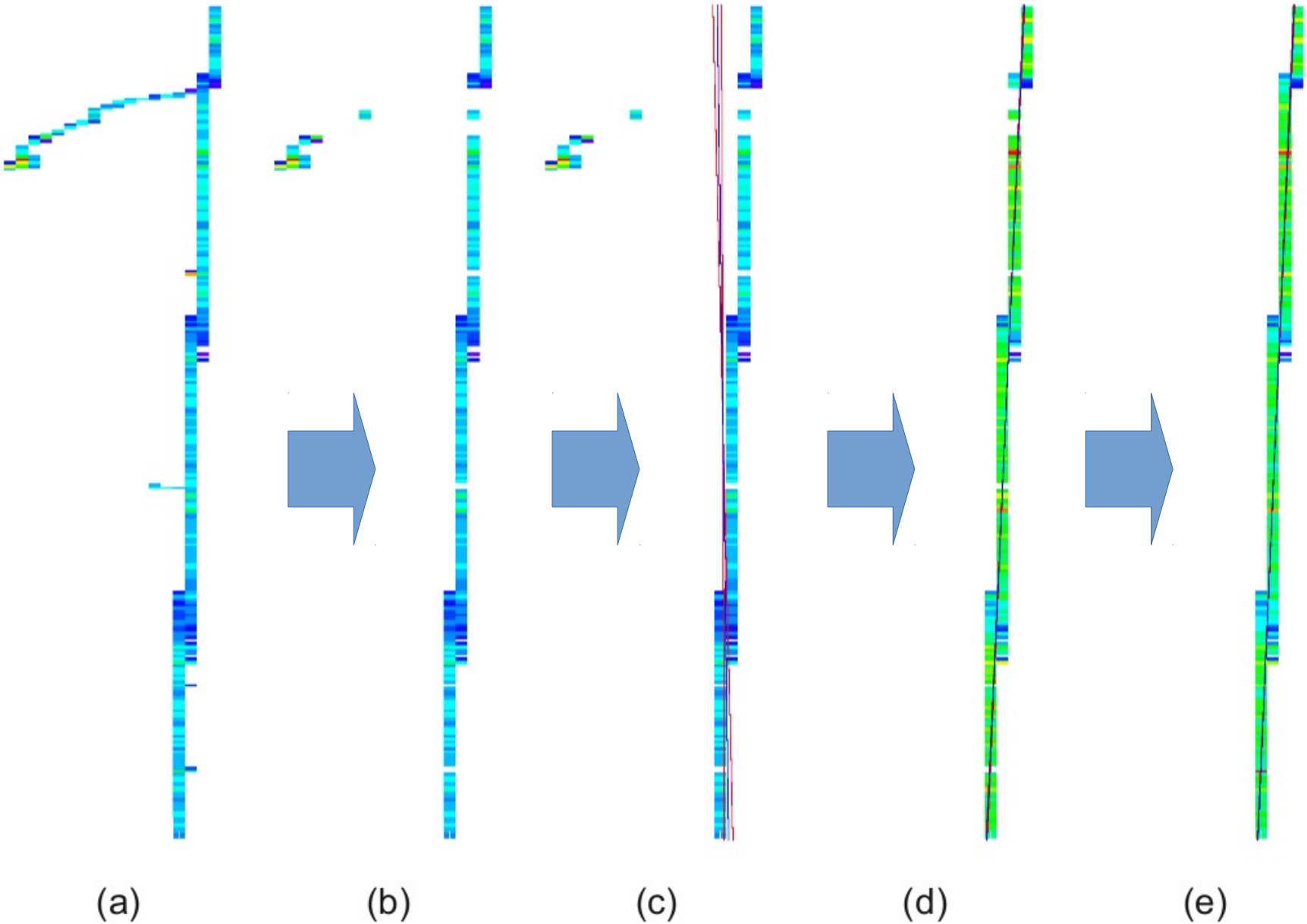


Spectacular digital tracks



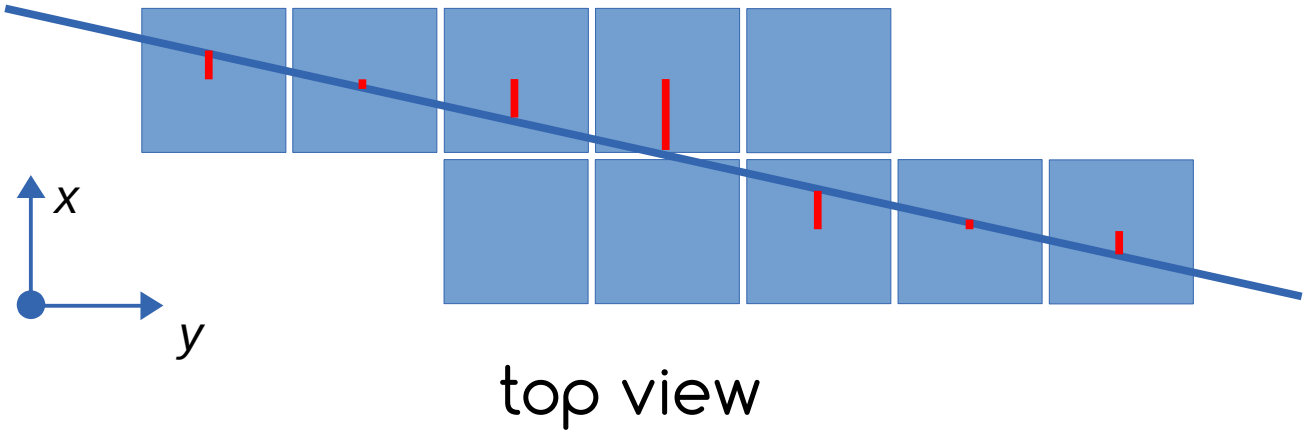
Energy deposit information in each pixel!

Track "cleaning" and fitting

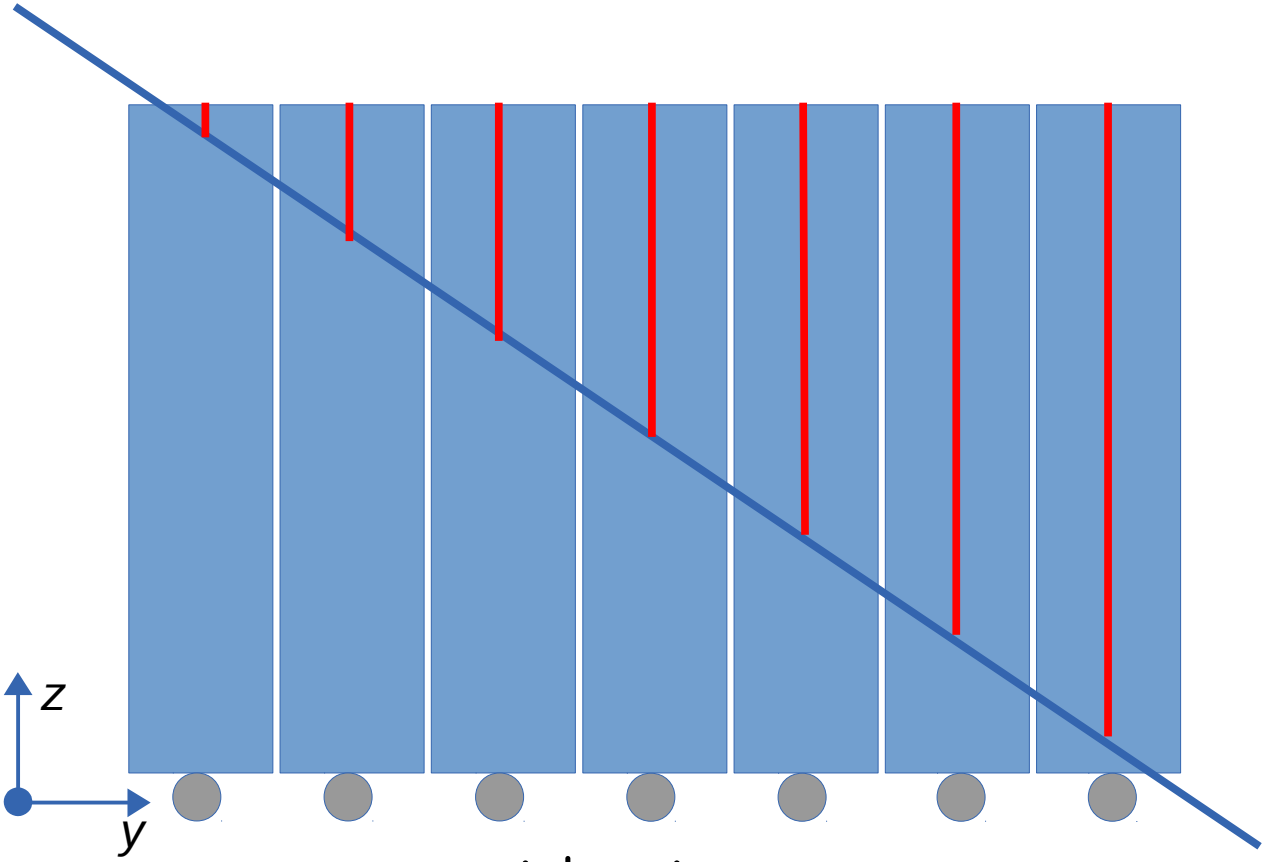


Remove delta rays and fit

Reaching sub-pixel resolution



top view

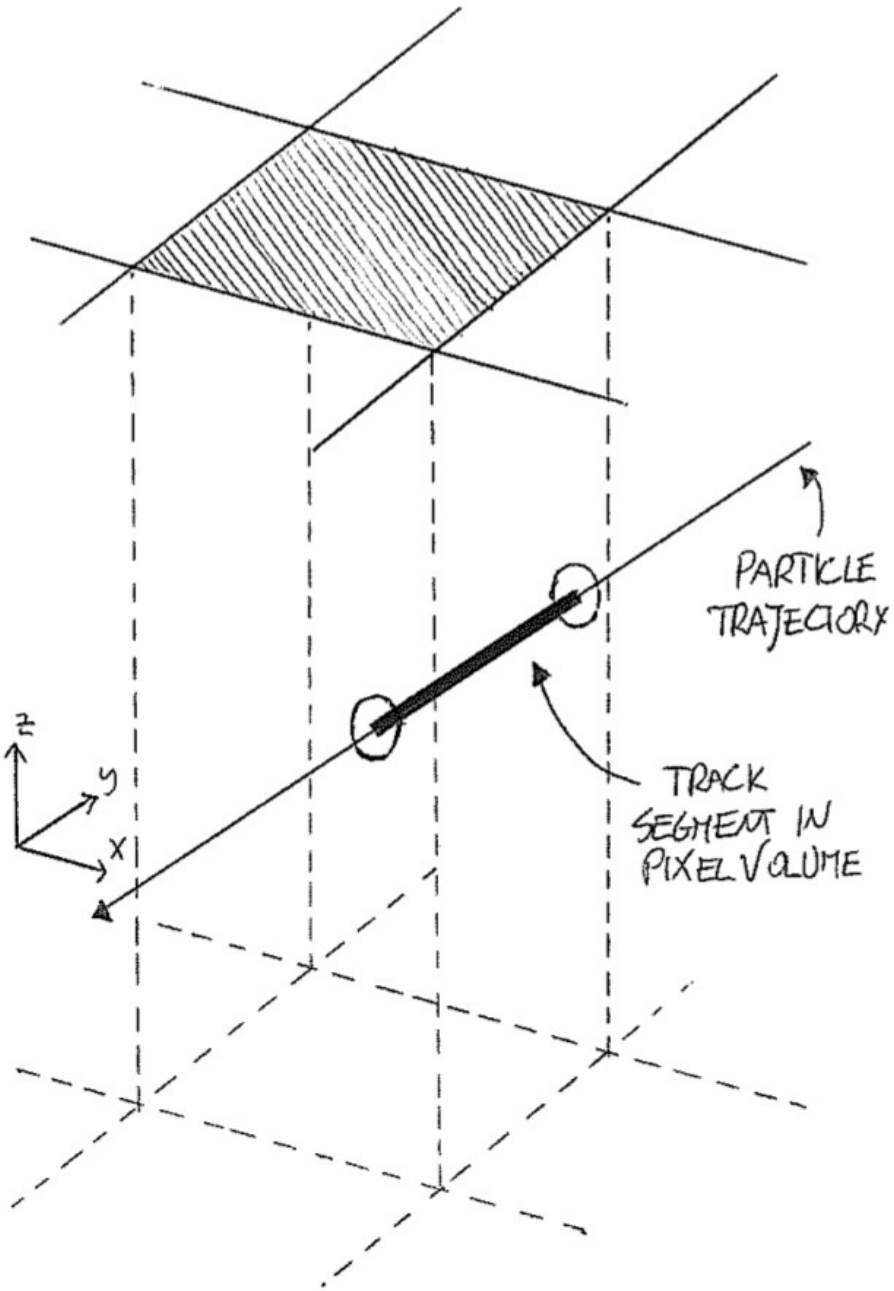


side view

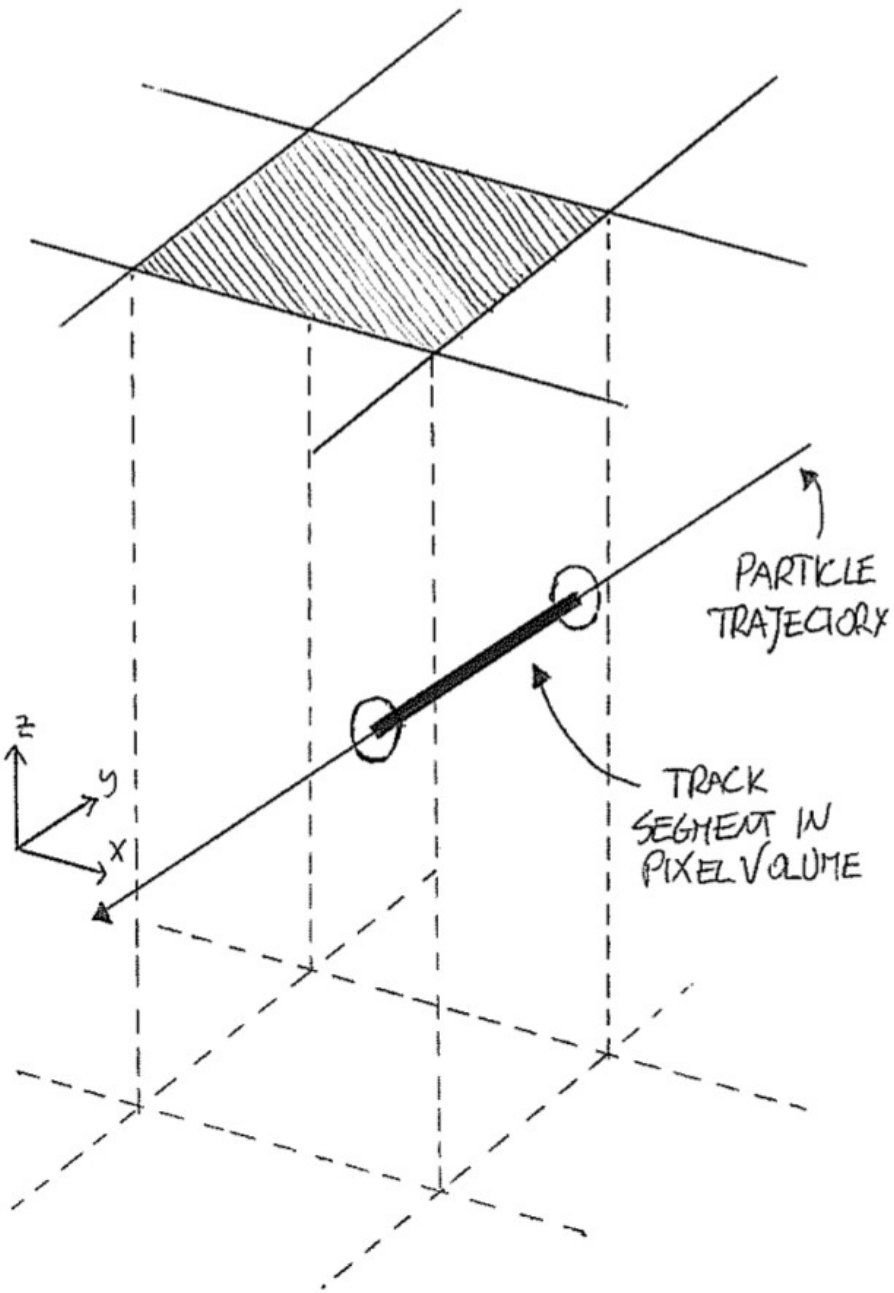
$\Delta x \sim$ um

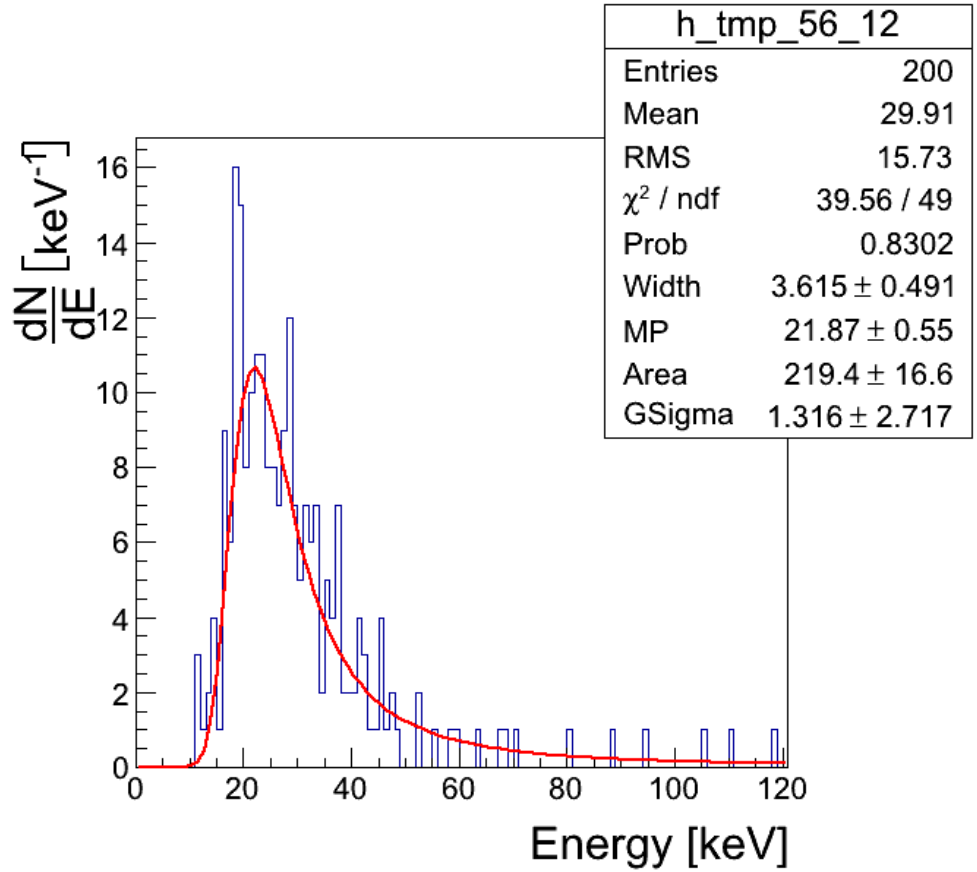
$\Delta z <$ um

Measuring energy loss within pixel volume



Measuring energy loss within pixel volume

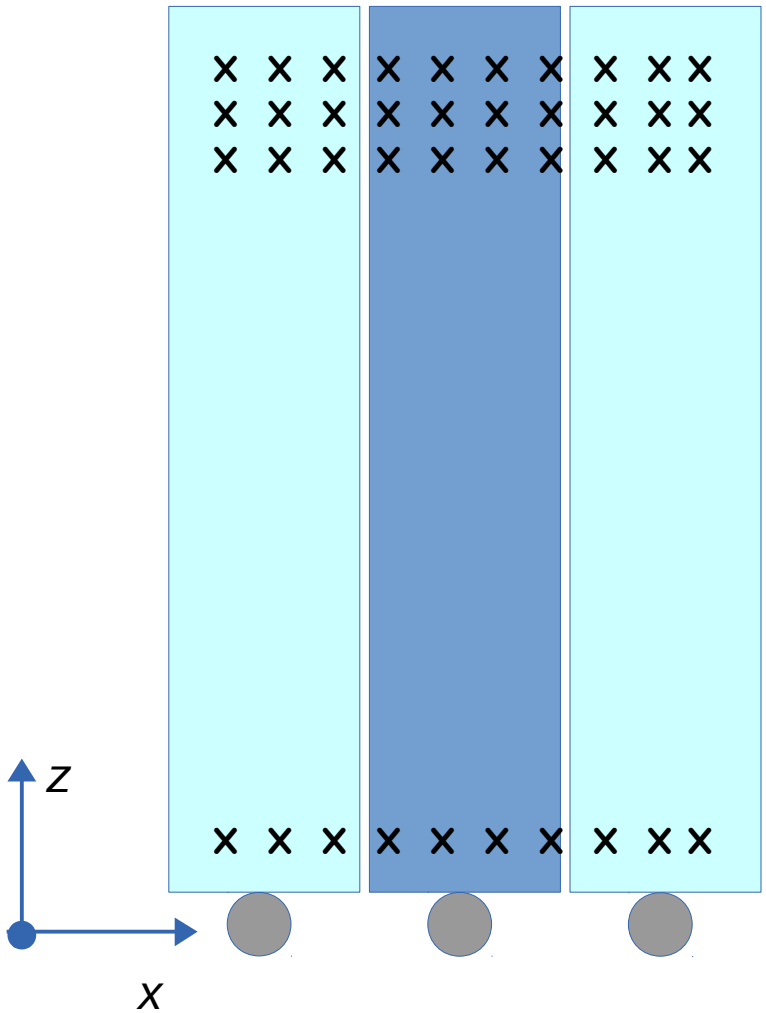




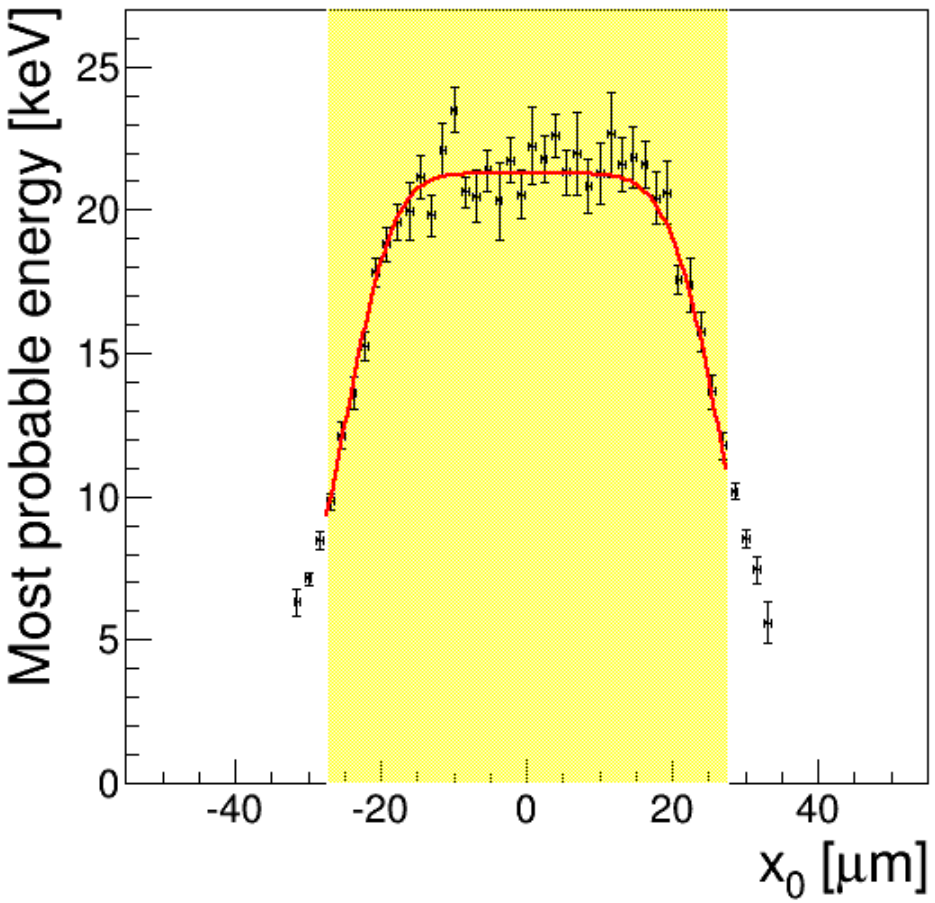
Landau distribution:
energy loss in a thin sensor

$$V = (x,y,z,E)$$

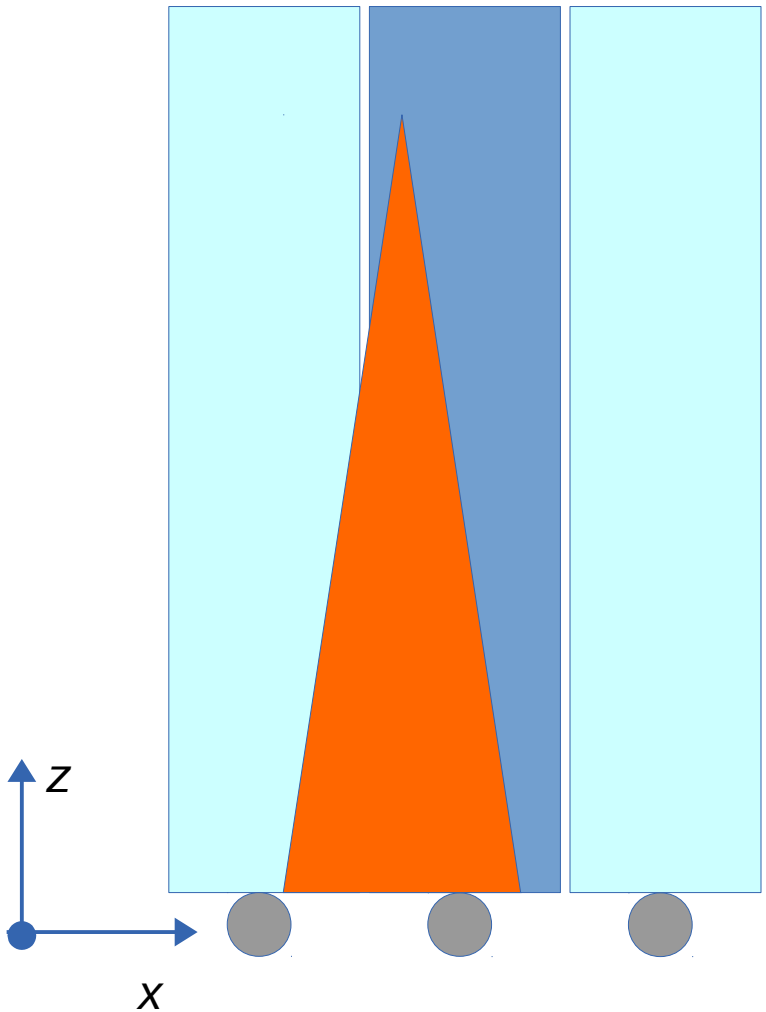
Looking at charge sharing

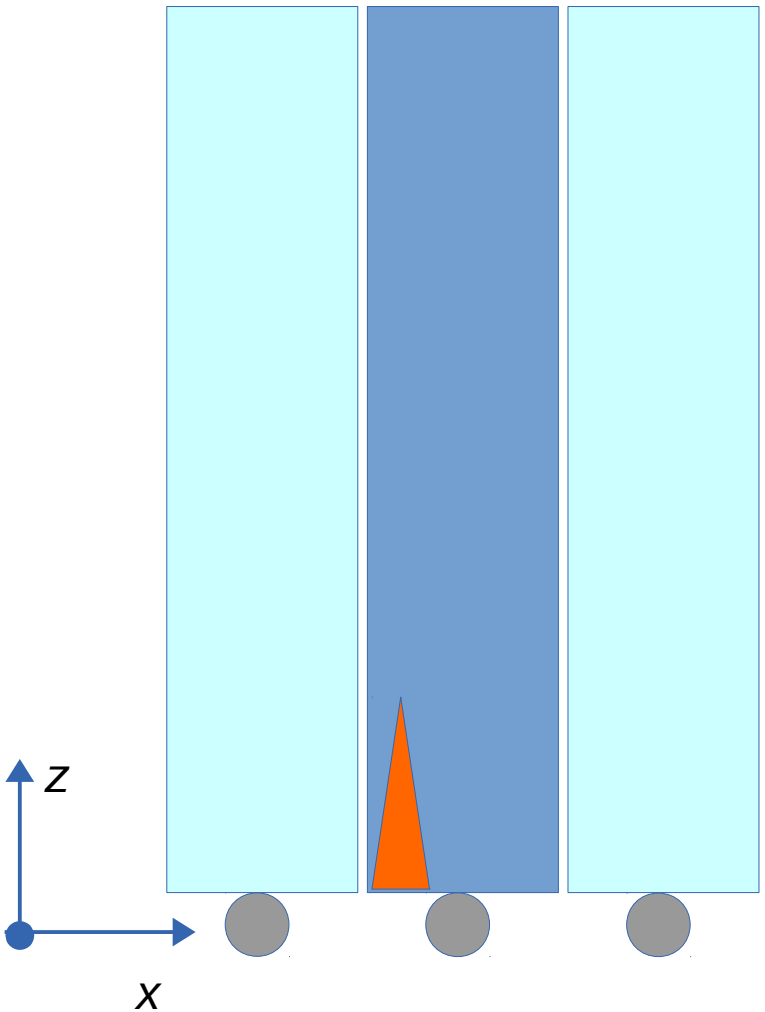


$z_0 = (91.5 \pm 0.9)\ \mu m$



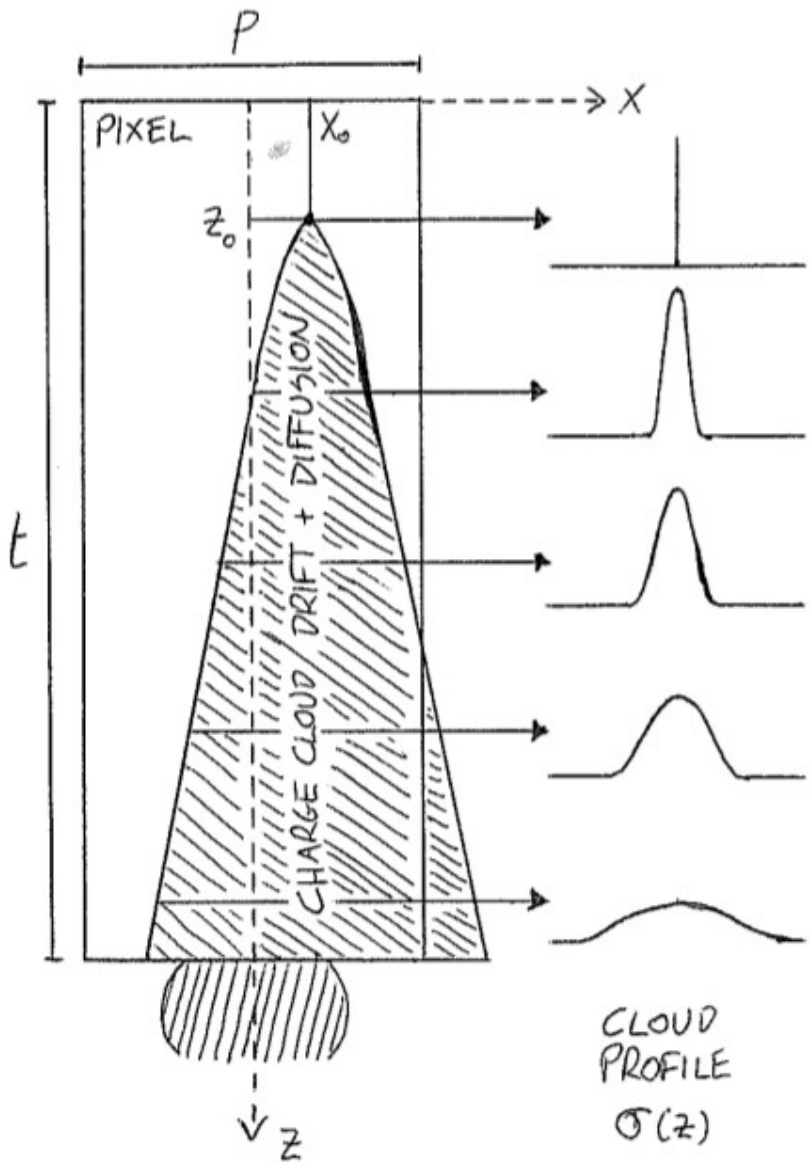
Charge sharing at different depths





These data contain information about the shape of the charge cloud

Charge transport model



1 – solve diffusion for an elongated distribution:

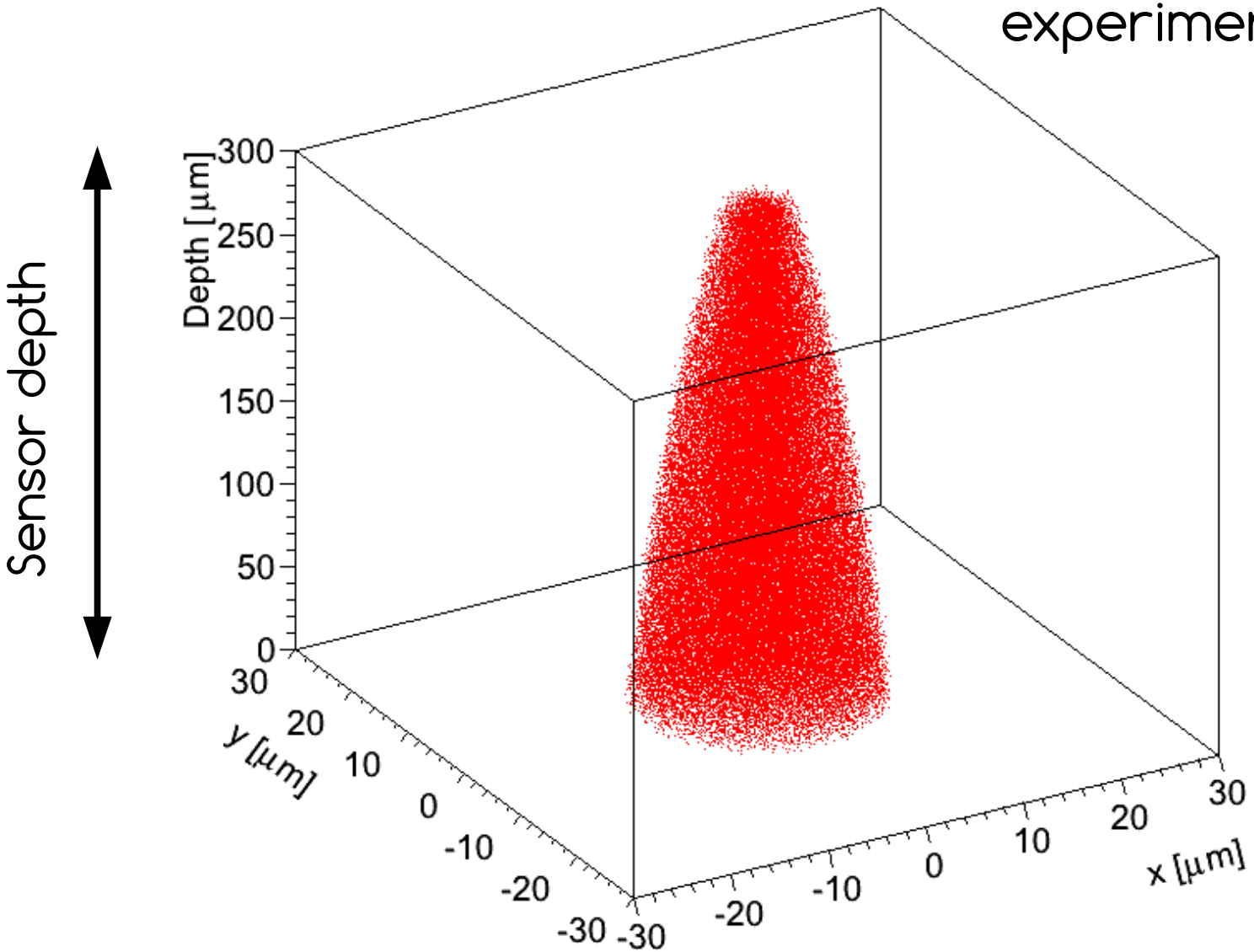
$$Q(x,y,z)=\frac{dQ_0}{y}\delta(x-x_0)\delta(z-z_0)$$

2 – add drift under electric field

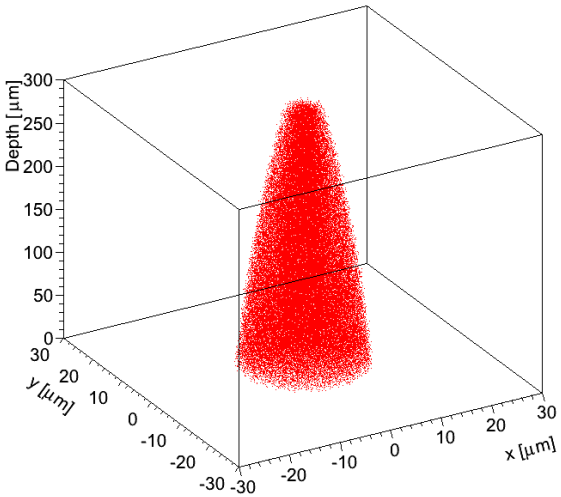
3 – fit the data!

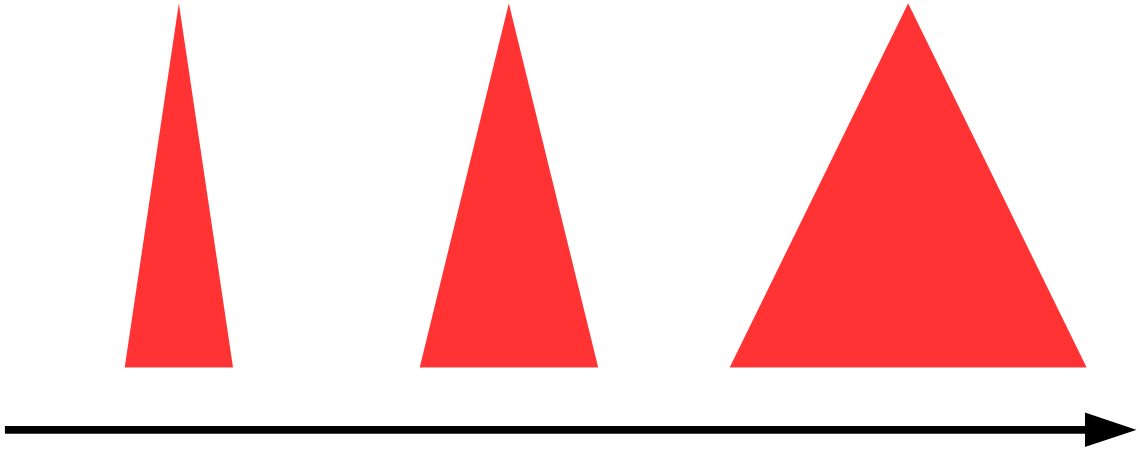
The result: expansion of the charge cloud

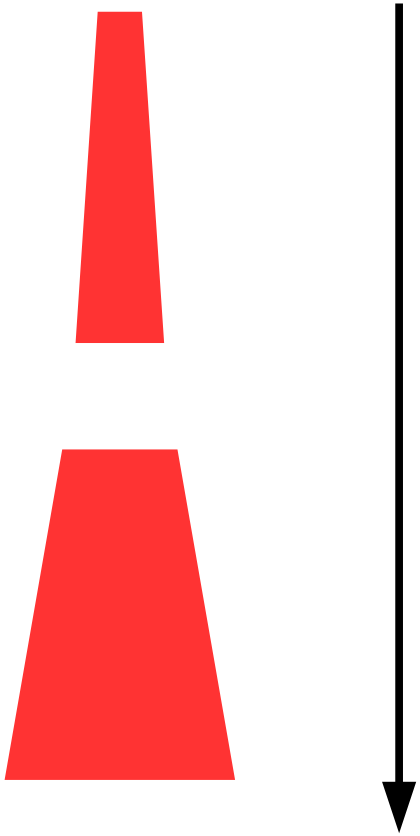
From fit to experimental data



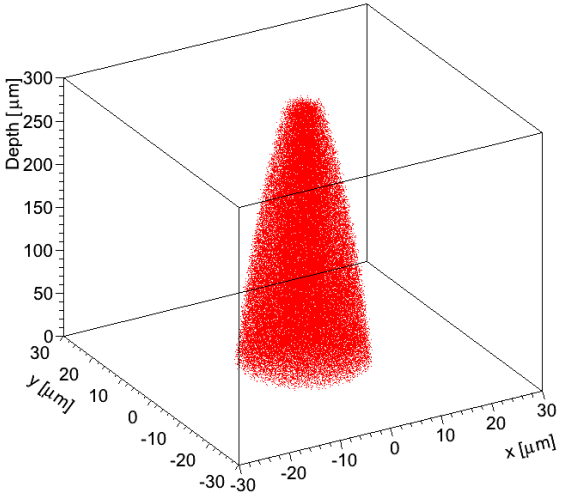
Adjusting the model parameters

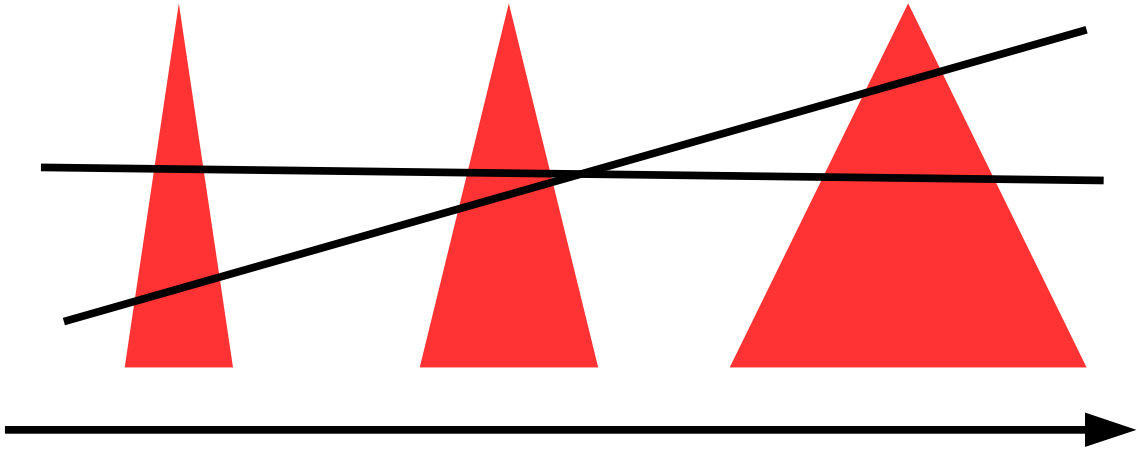


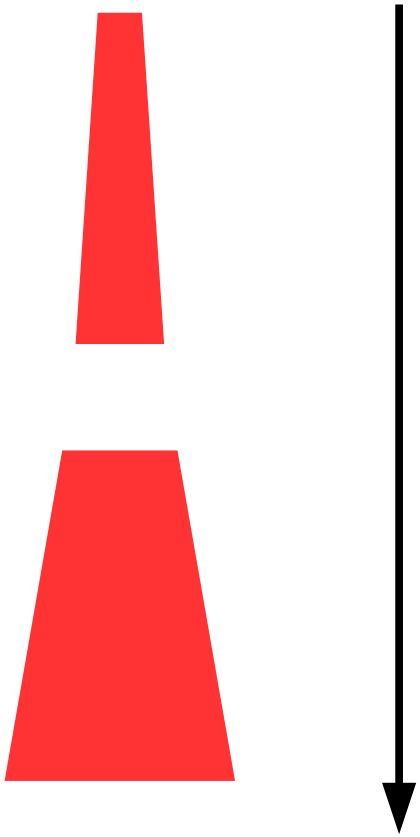




Adjusting the model parameters

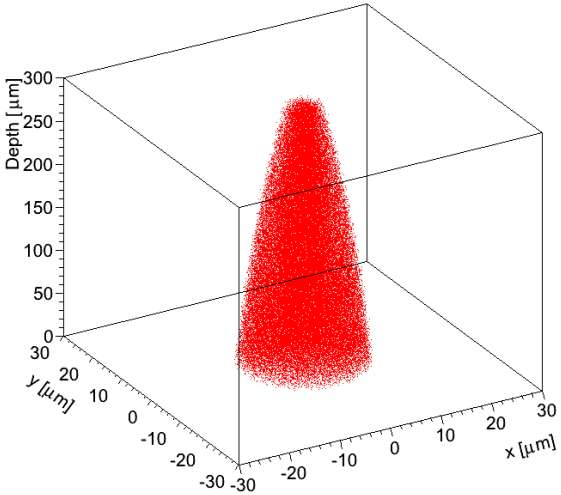


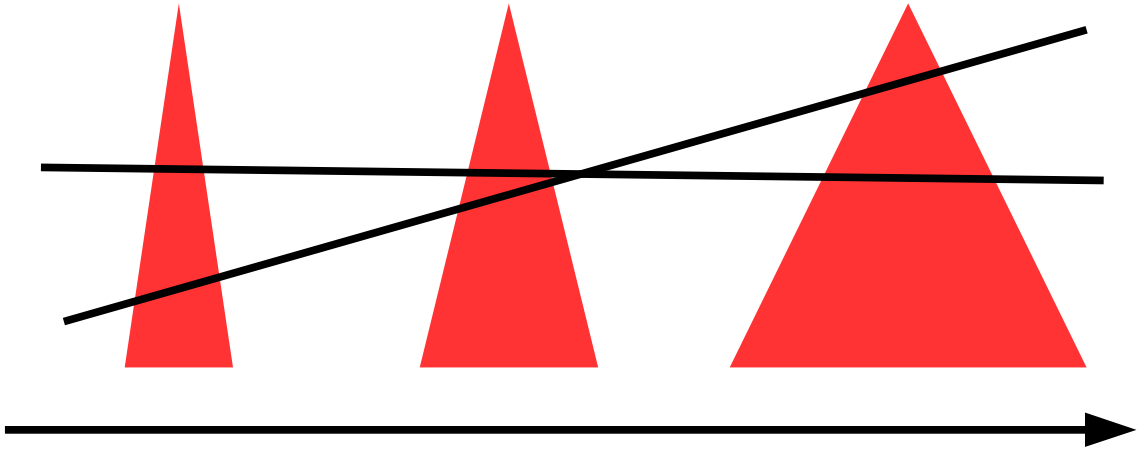


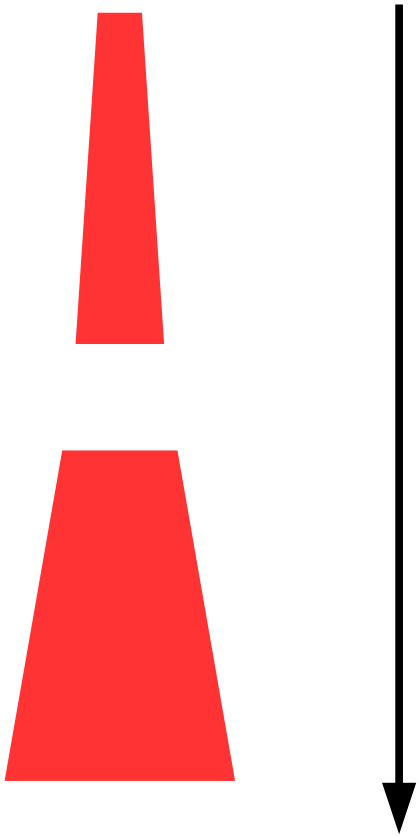


$$\langle x \rangle = \sqrt{2Dt}$$

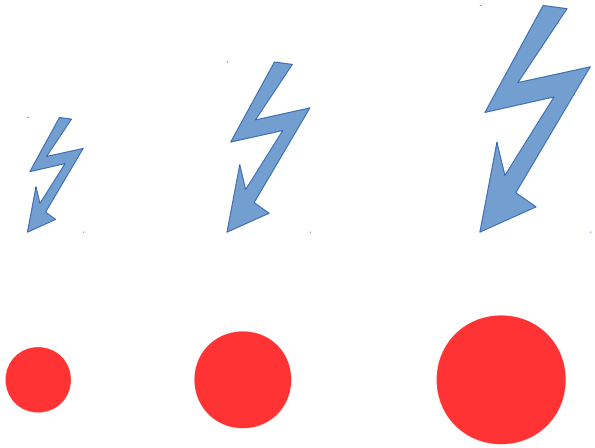
Adjusting the model parameters



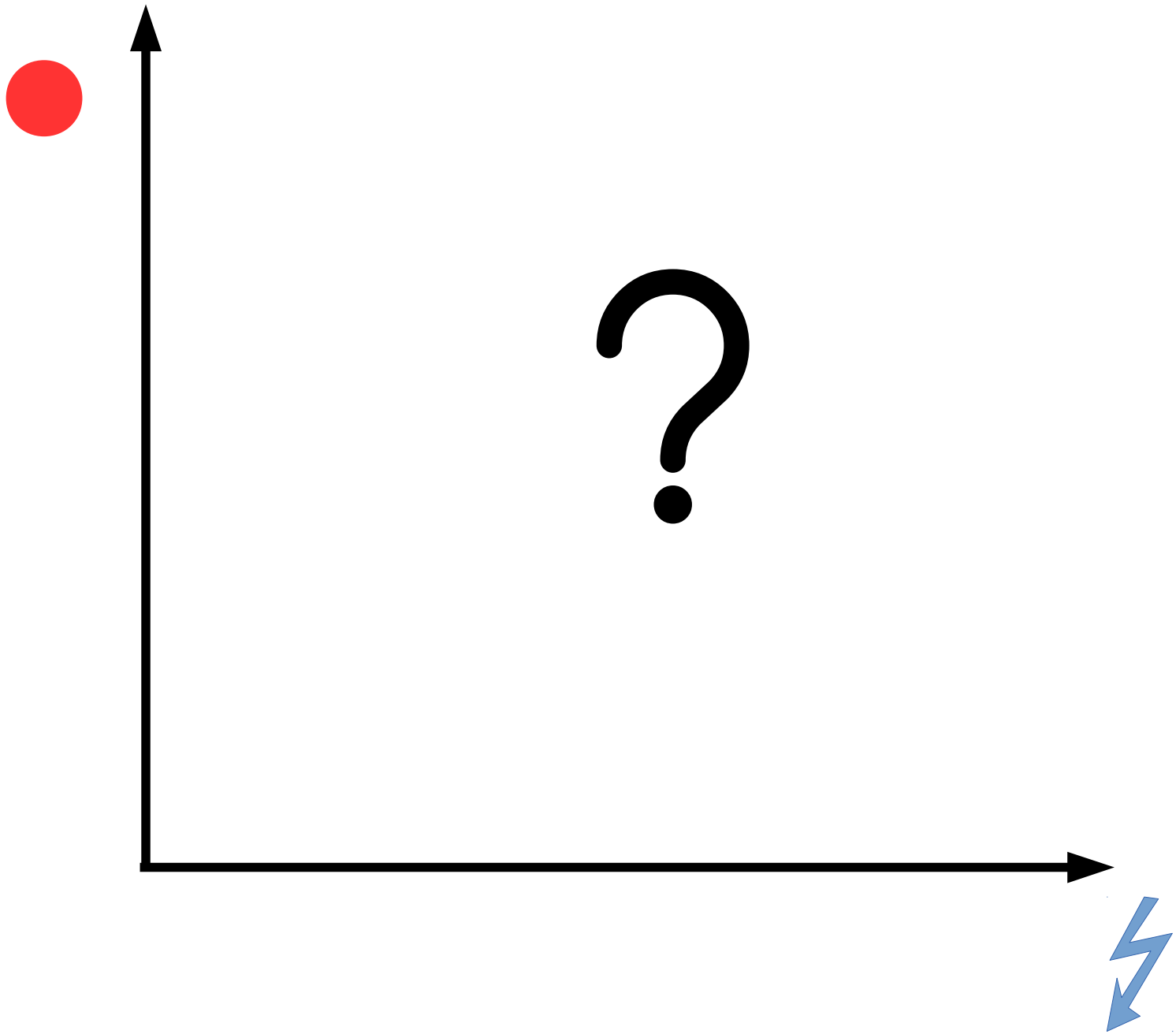




$$\langle x \rangle = \sqrt{2Dt}$$



Initial cloud size as a function of photon energy



Synchrotron test beam

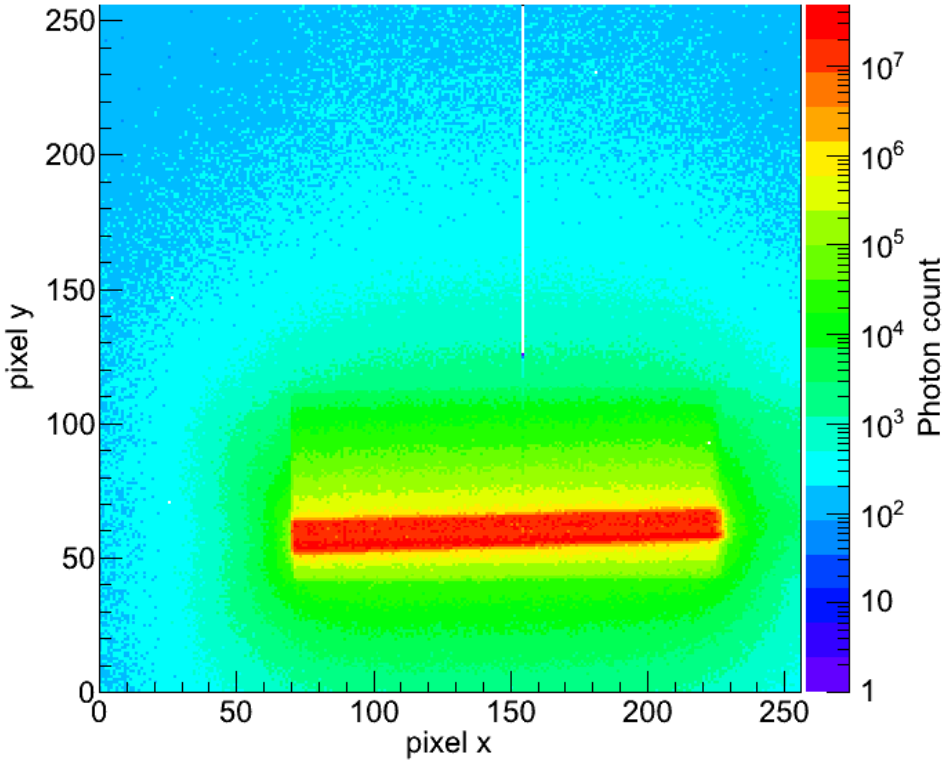
European Synchrotron Radiation Facility, Grenoble, France

Synchrotron test beam

Quite unusual conditions:

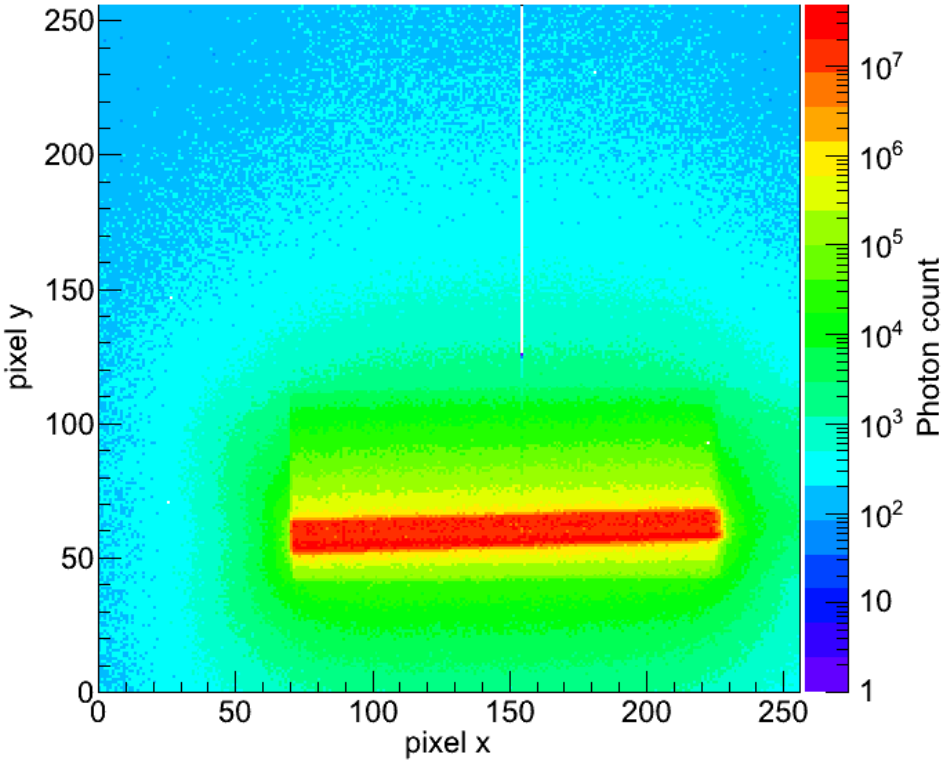
- Broad beam
- Energy scan
- Adjust optics at each energy

Radiation damage

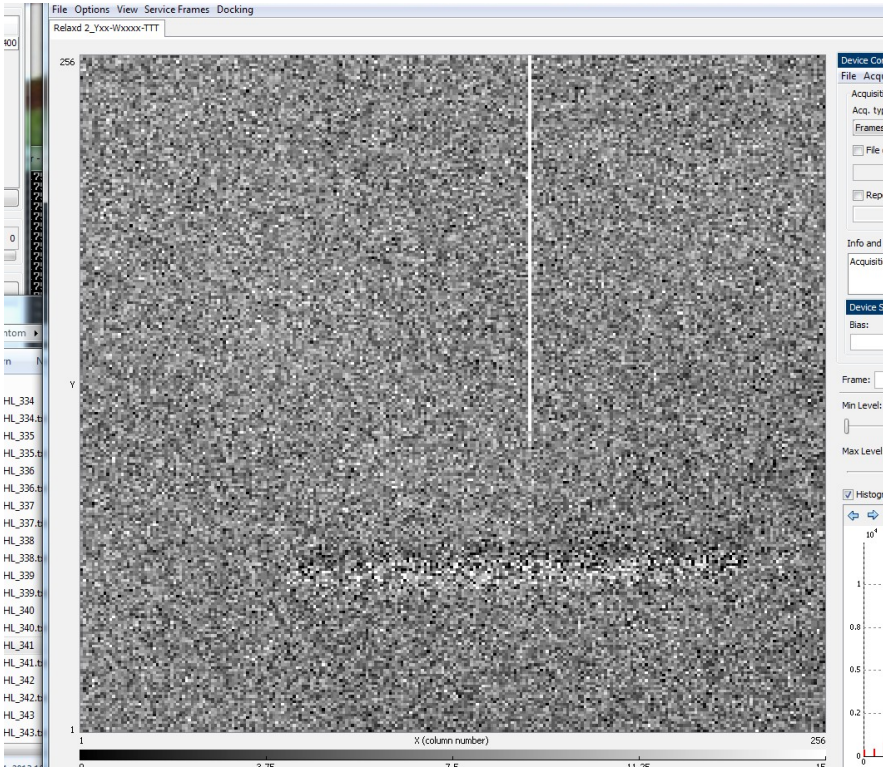


Beam spot during exposure

Radiation damage

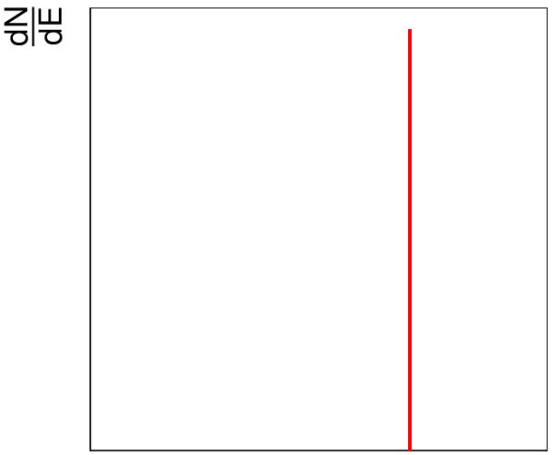


Beam spot during exposure

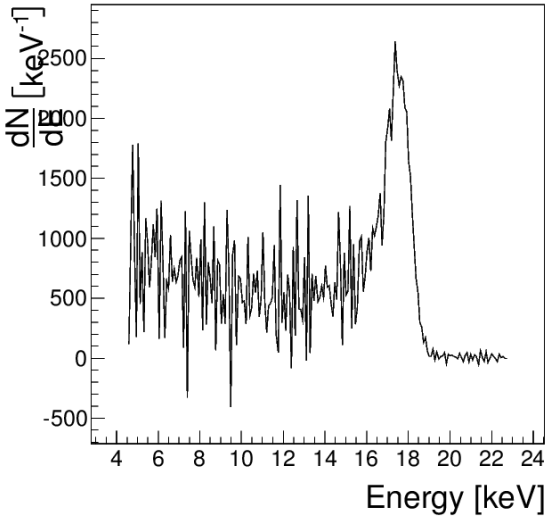


Uniform irradiation after test beam

Measurement and analysis technique

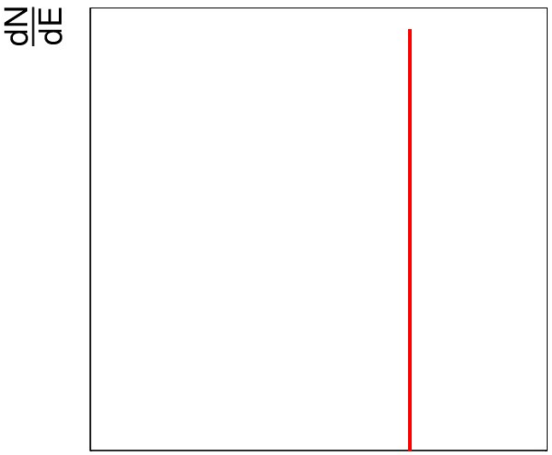


Monochromatic source spectrum

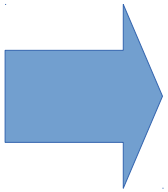


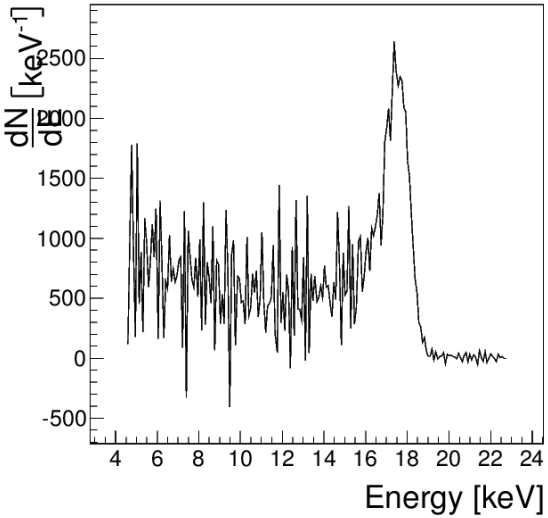
Calibrated pixel spectrum

Measurement and analysis technique

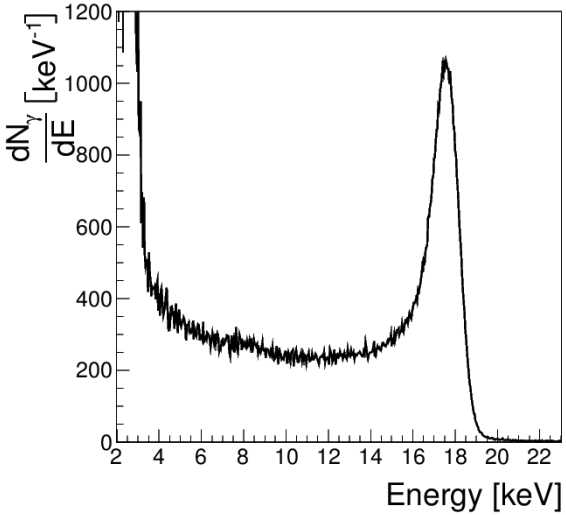


Monochromatic source spectrum



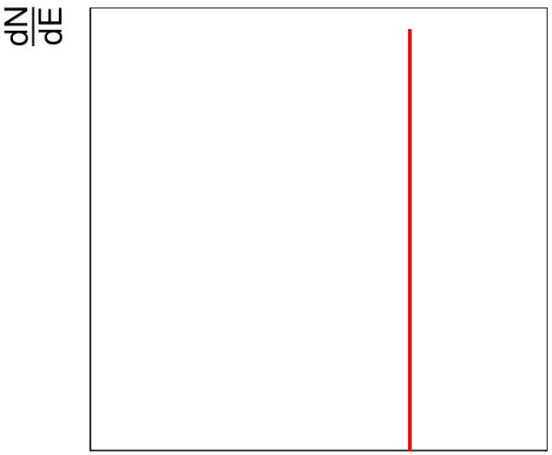


Calibrated pixel spectrum

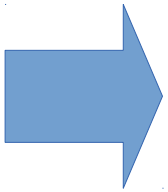


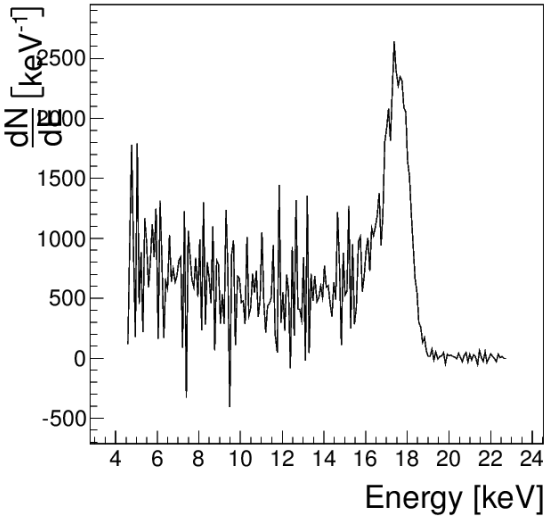
Summed pixel spectra

Measurement and analysis technique

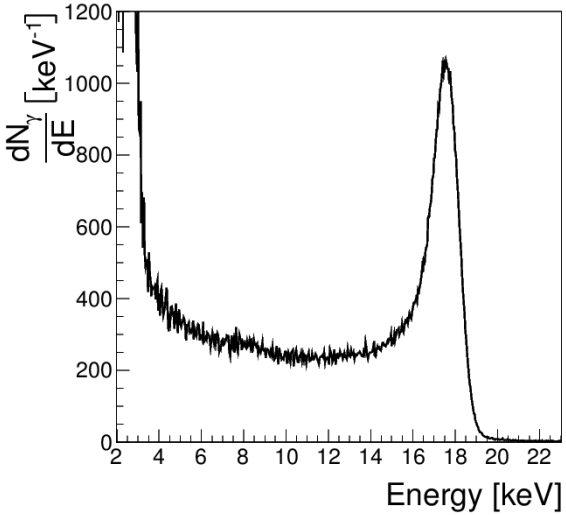


Monochromatic source spectrum

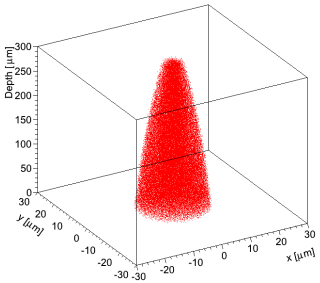




Calibrated pixel spectrum

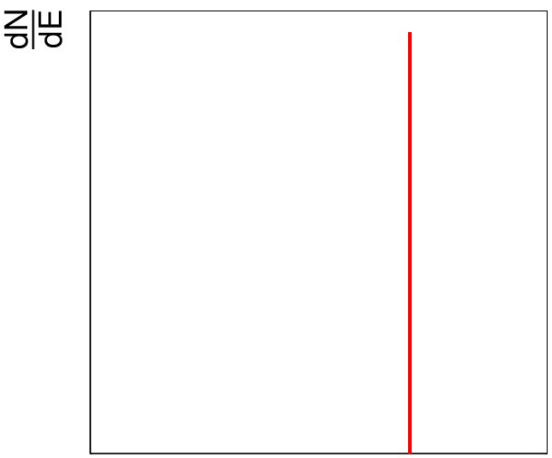


Summed pixel spectra

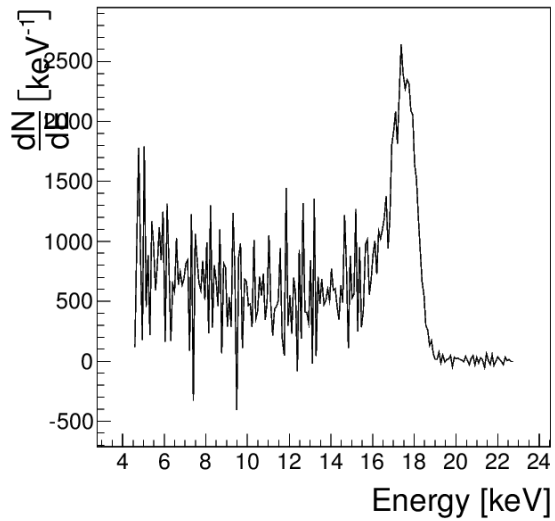


Now use the model
Leave σ_0 free

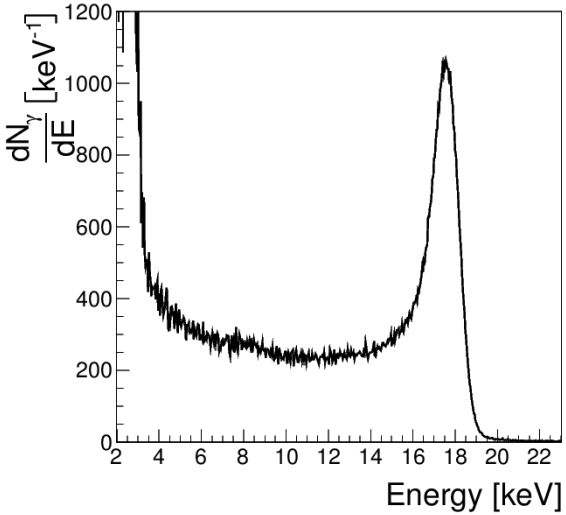
Measurement and analysis technique



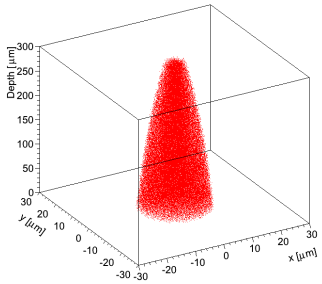
Monochromatic source spectrum



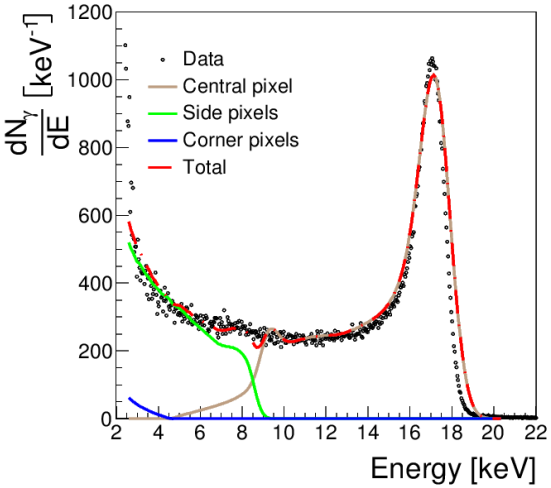
Calibrated pixel spectrum



Summed pixel spectra

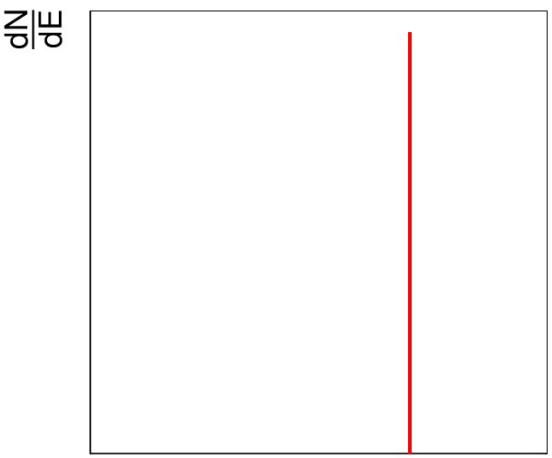


Now use the model
Leave σ_0 free

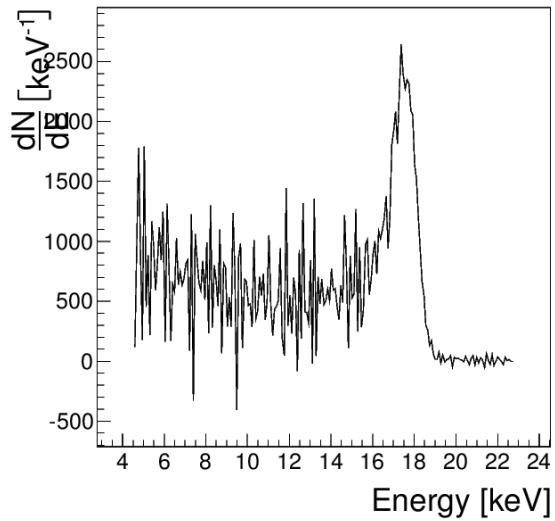


Fit for σ_0

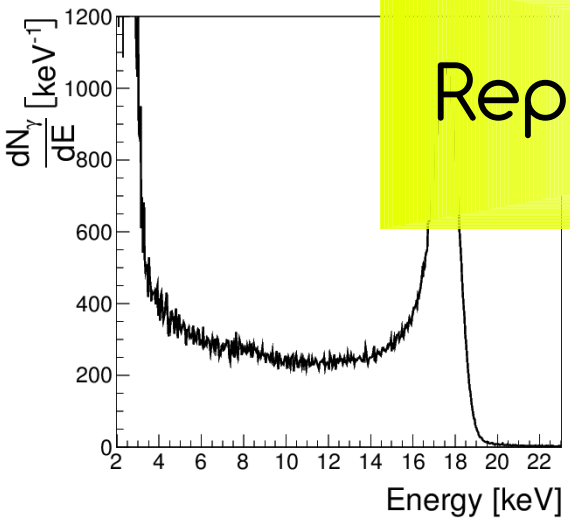
Measurement and analysis technique



Monochromatic source spectrum

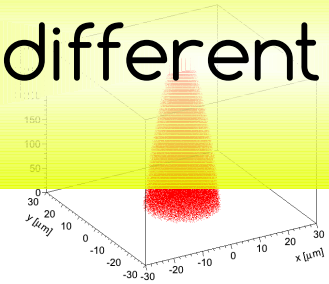


Calibrated pixel spectrum

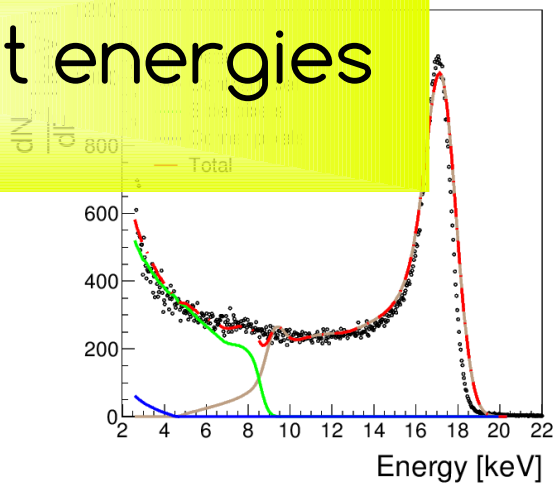


Summed pixel spectra

Repeat for different input energies

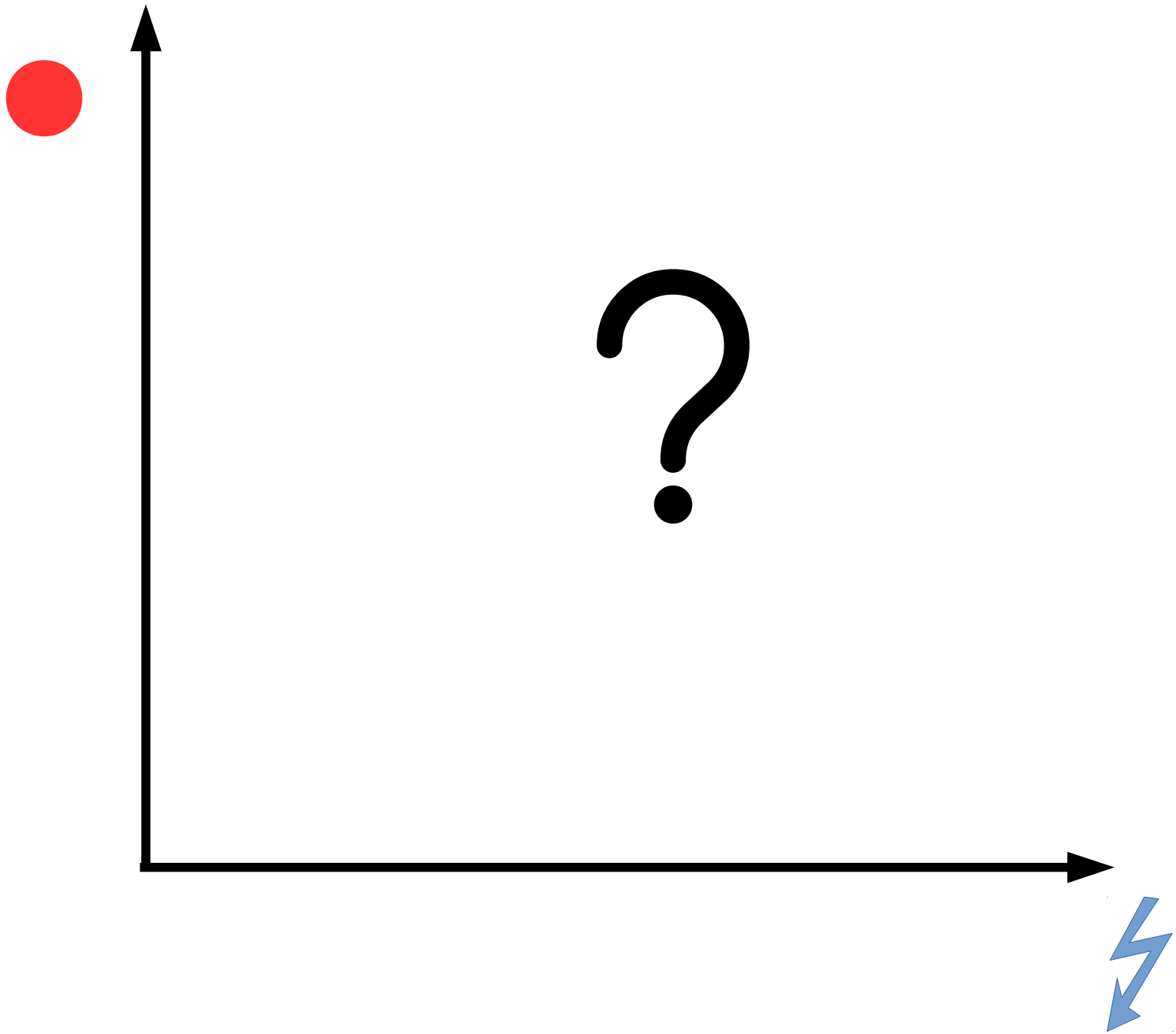


Now use the model
Leave σ_0 free

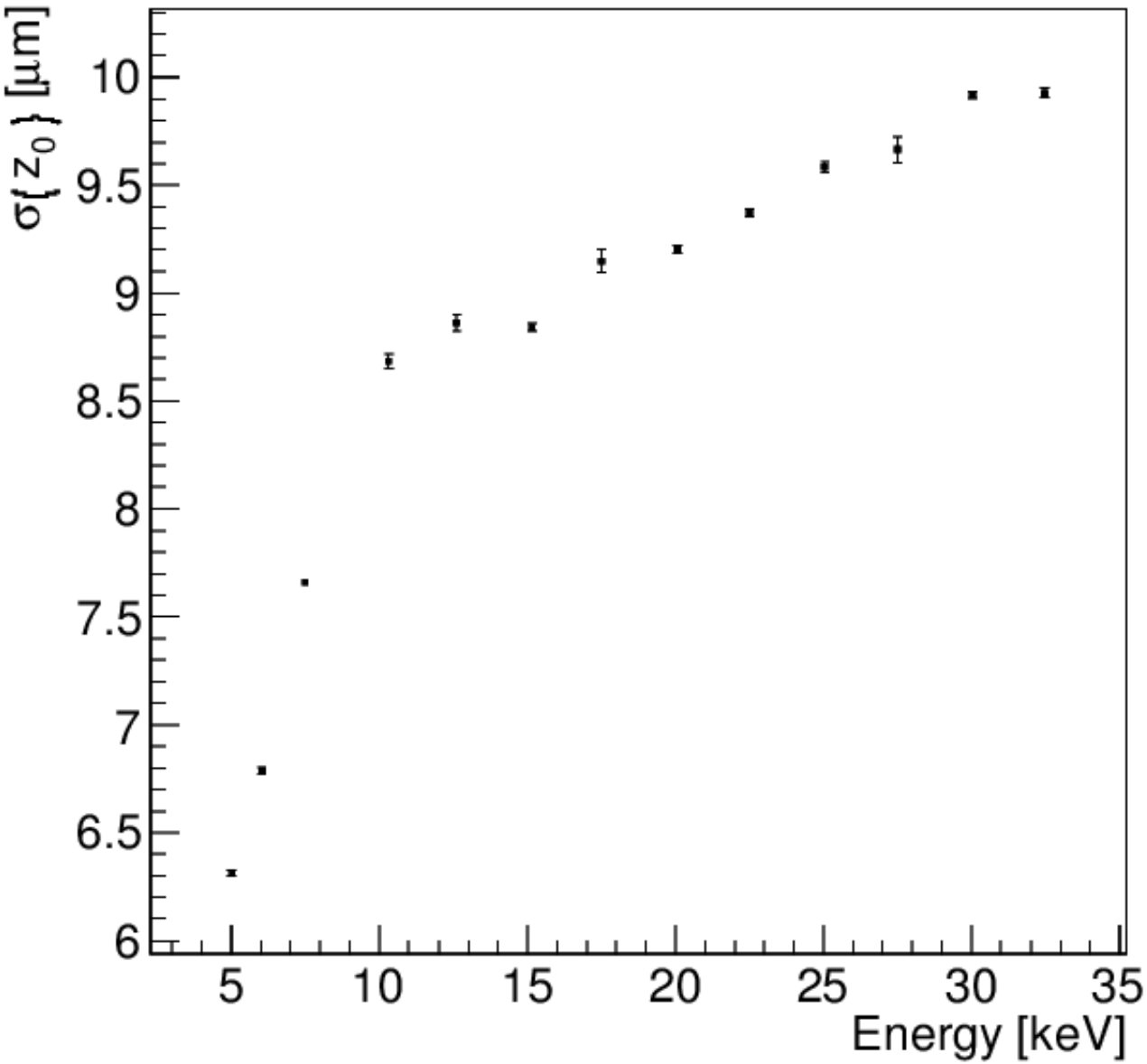


Fit for σ_0

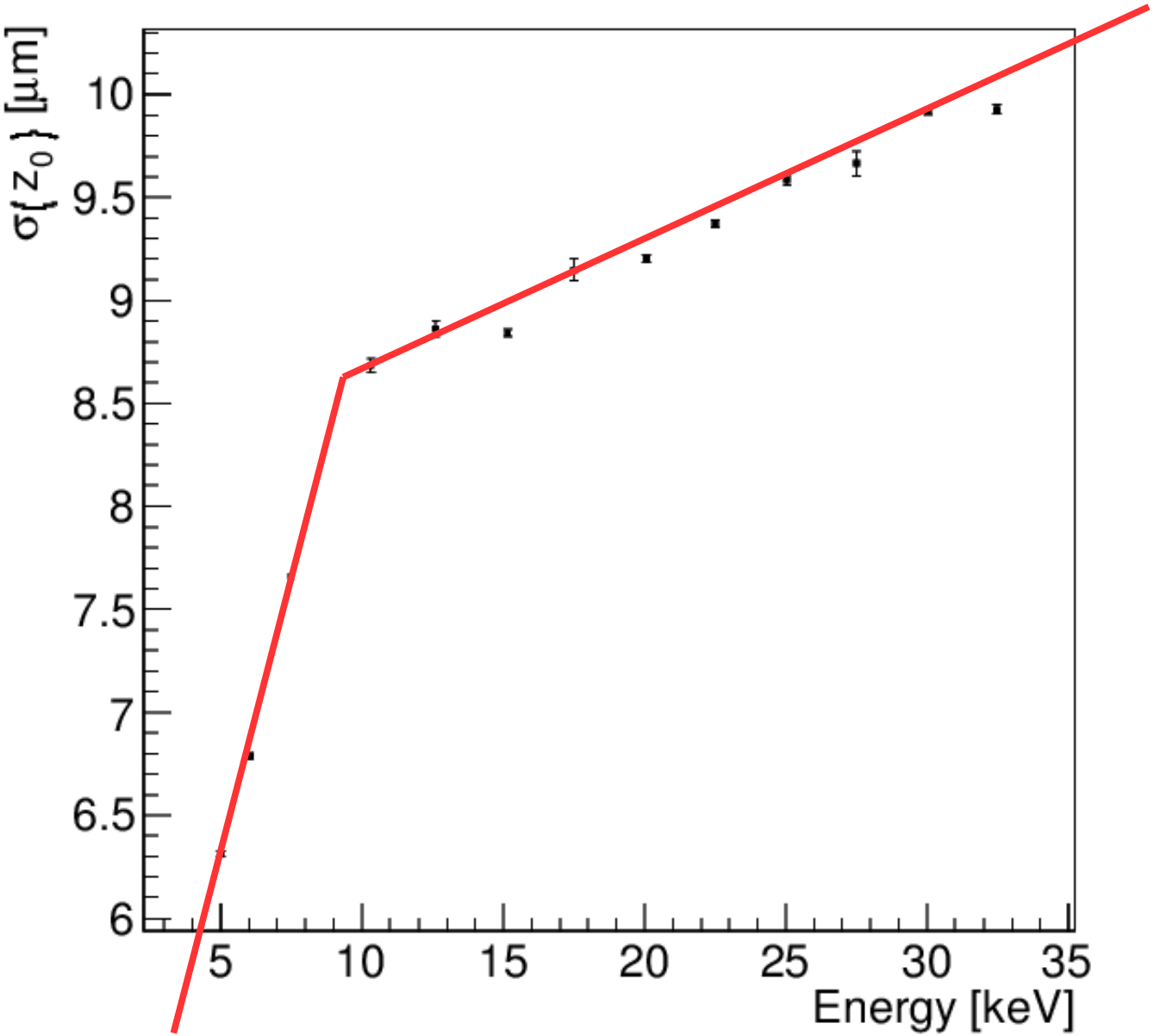
Initial cloud size as a function of photon energy



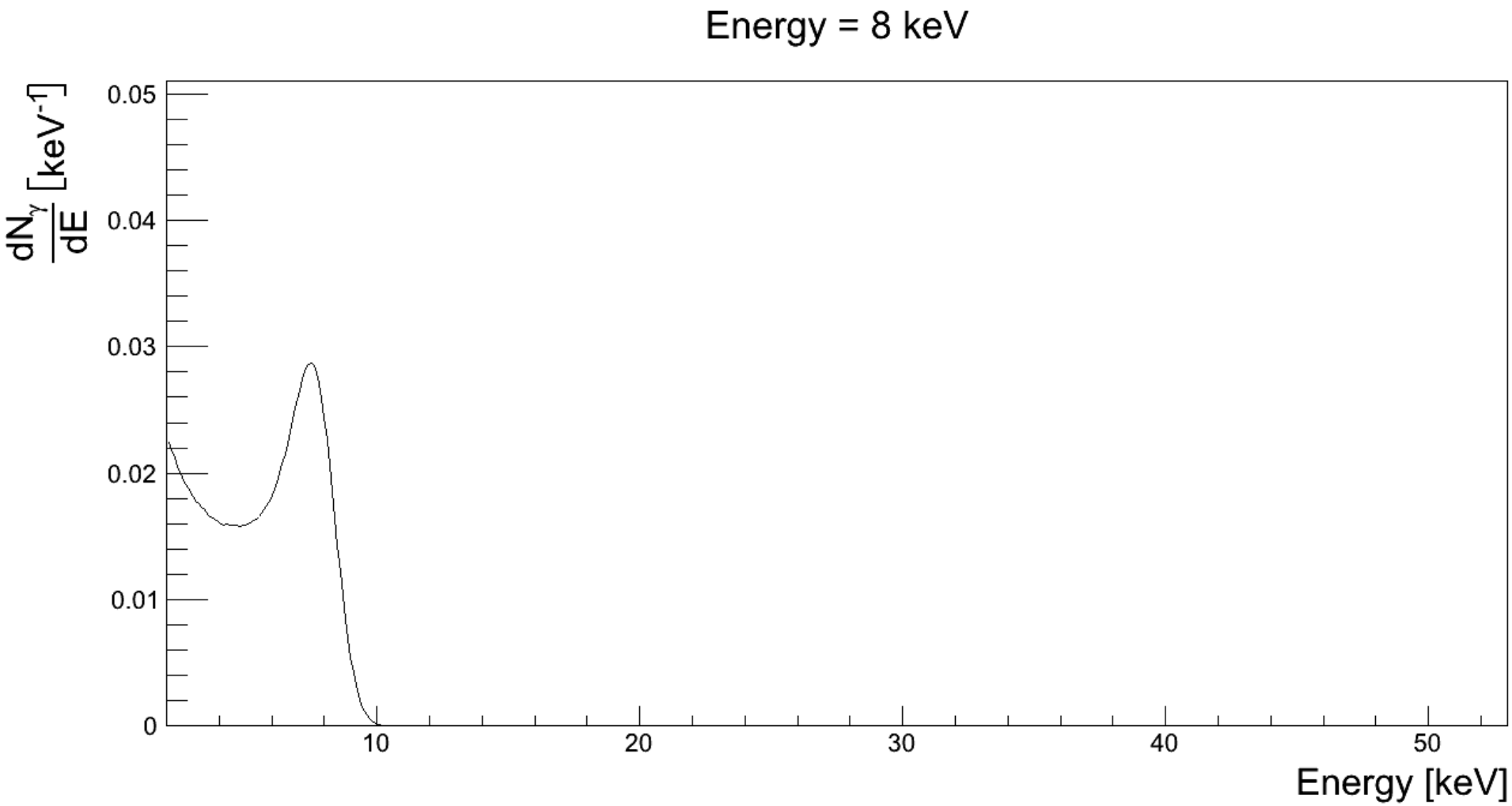
Initial cloud size as a function of photon energy



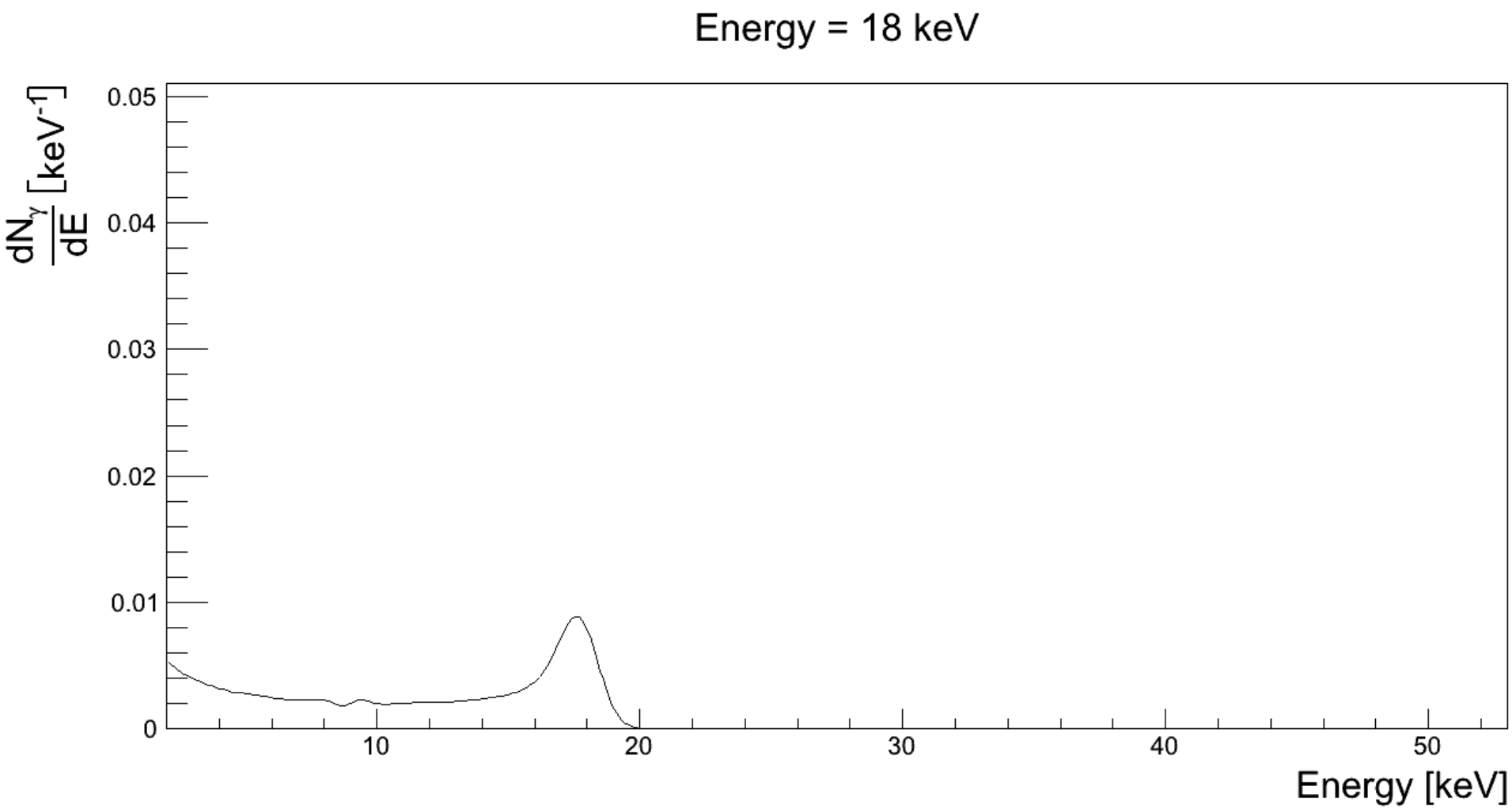
Initial cloud size as a function of photon energy



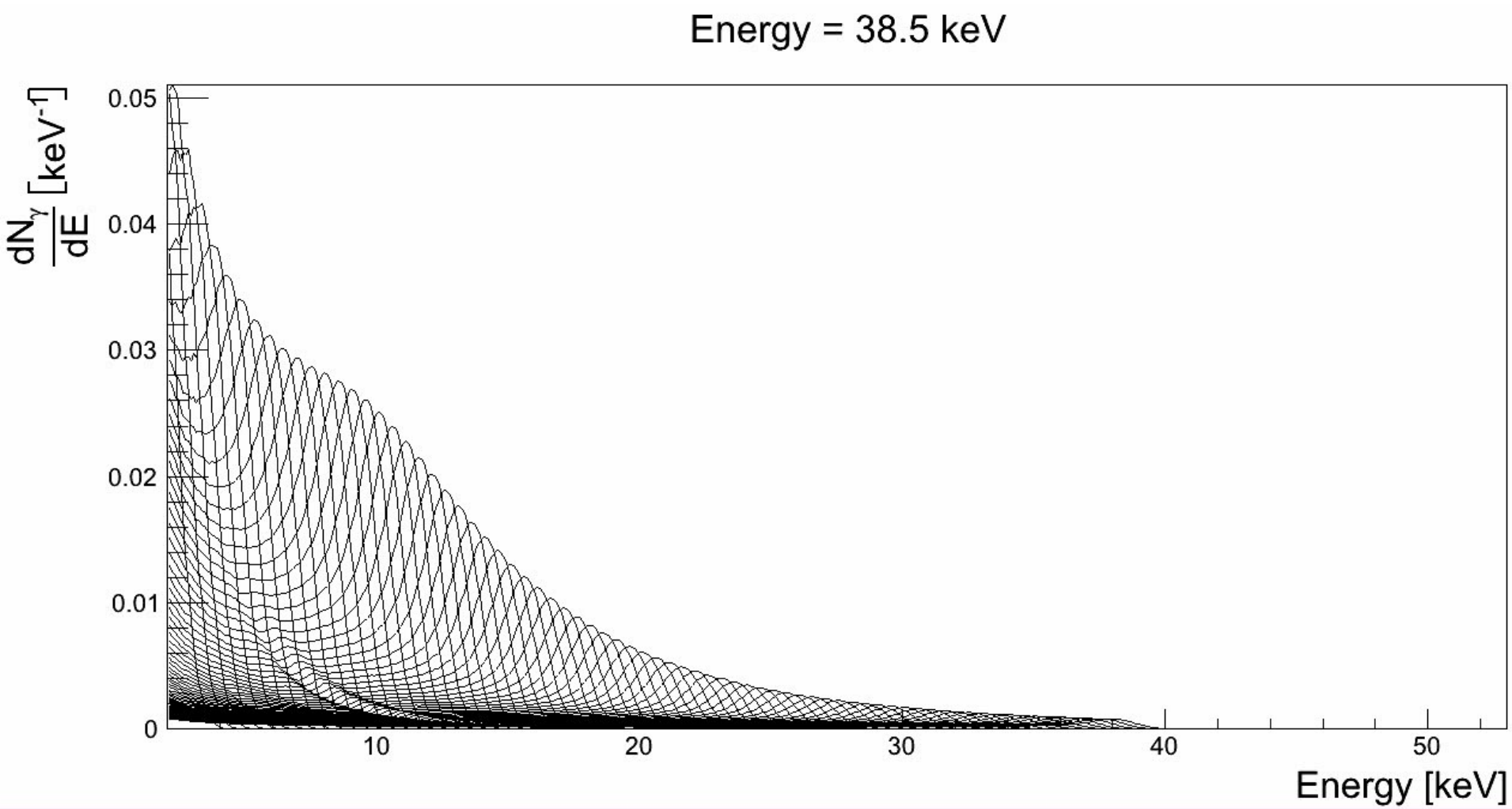
Compute monochromatic spectrum at given energy



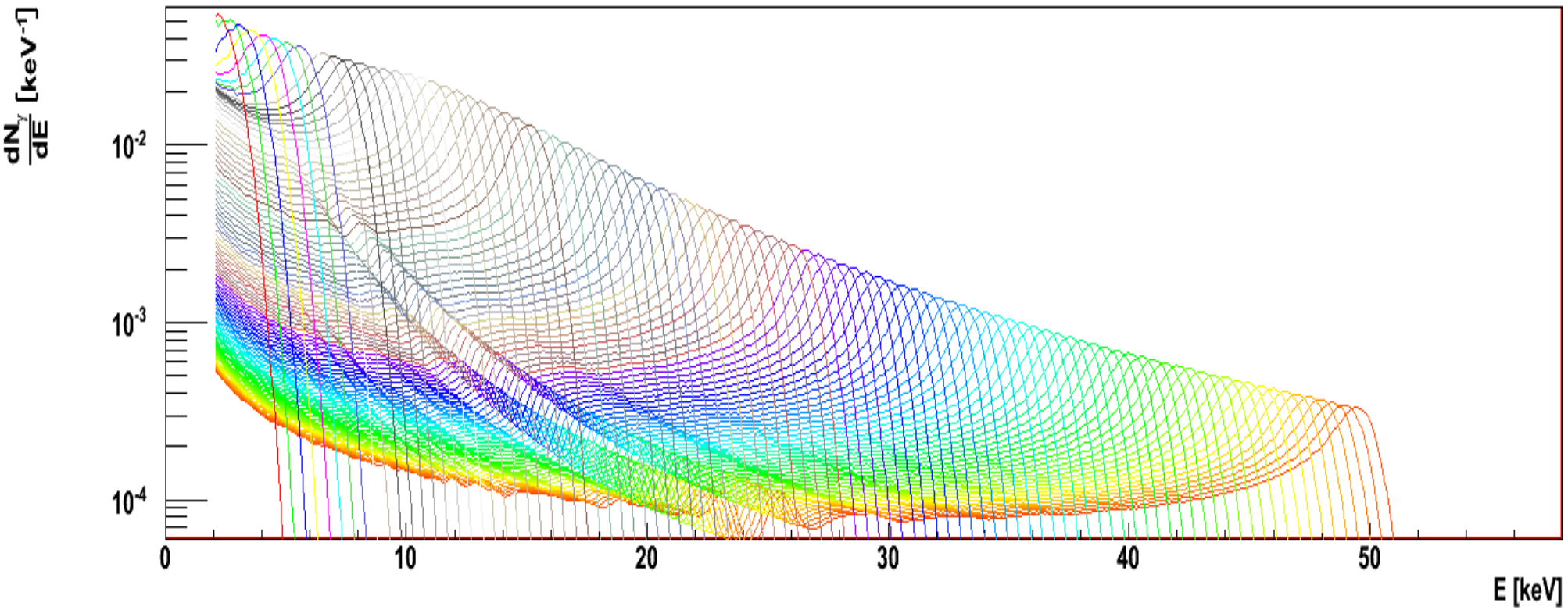
Compute monochromatic spectrum at given energy



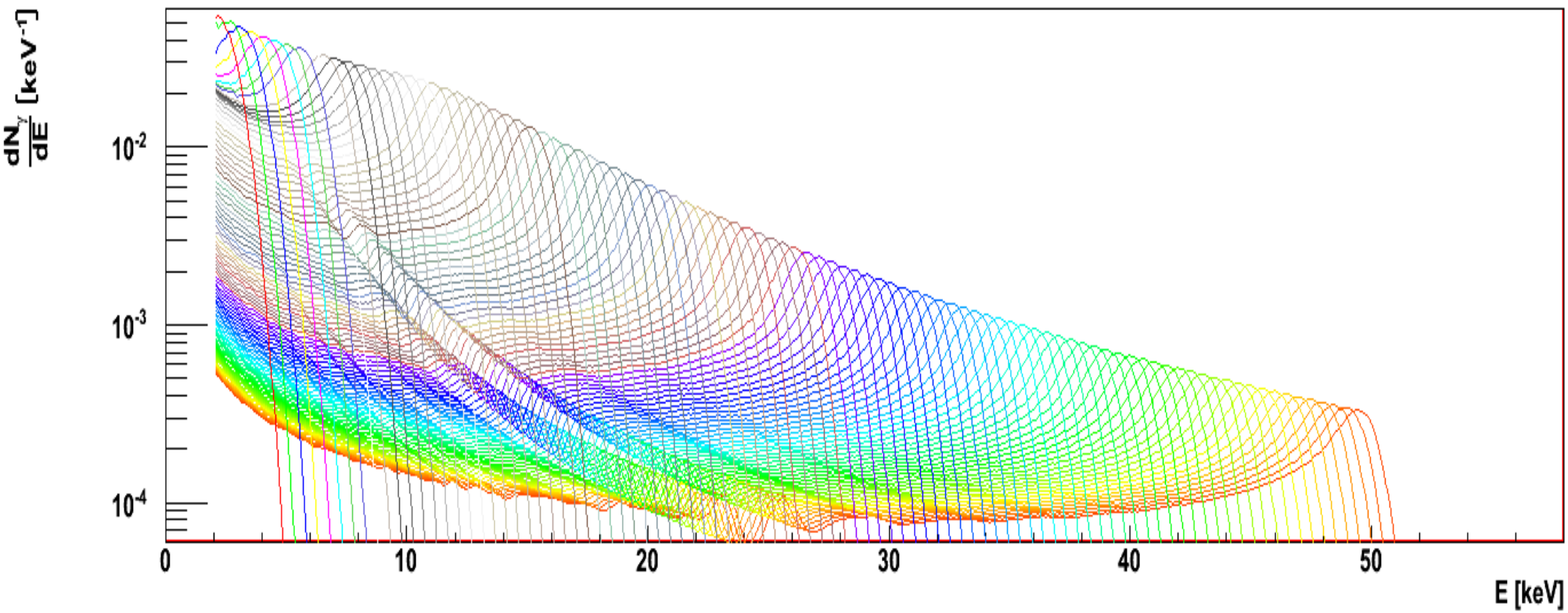
Compute monochromatic spectrum at given energy



Compute monochromatic spectrum at given energy

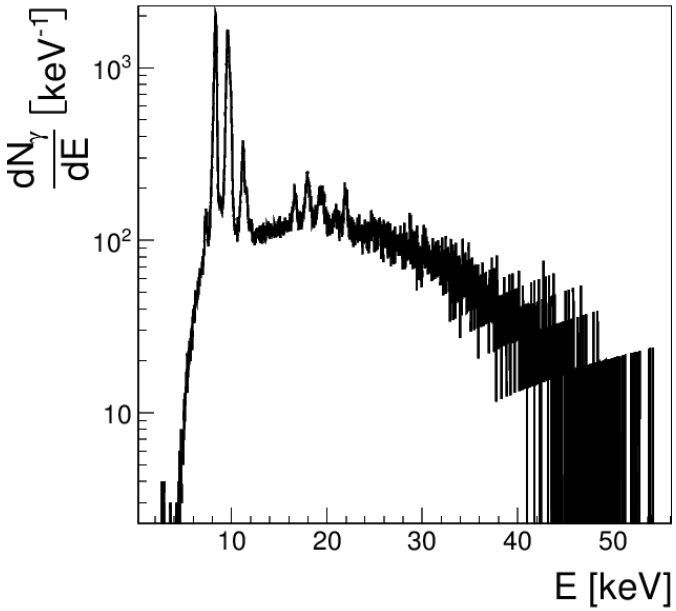


The energy response function!

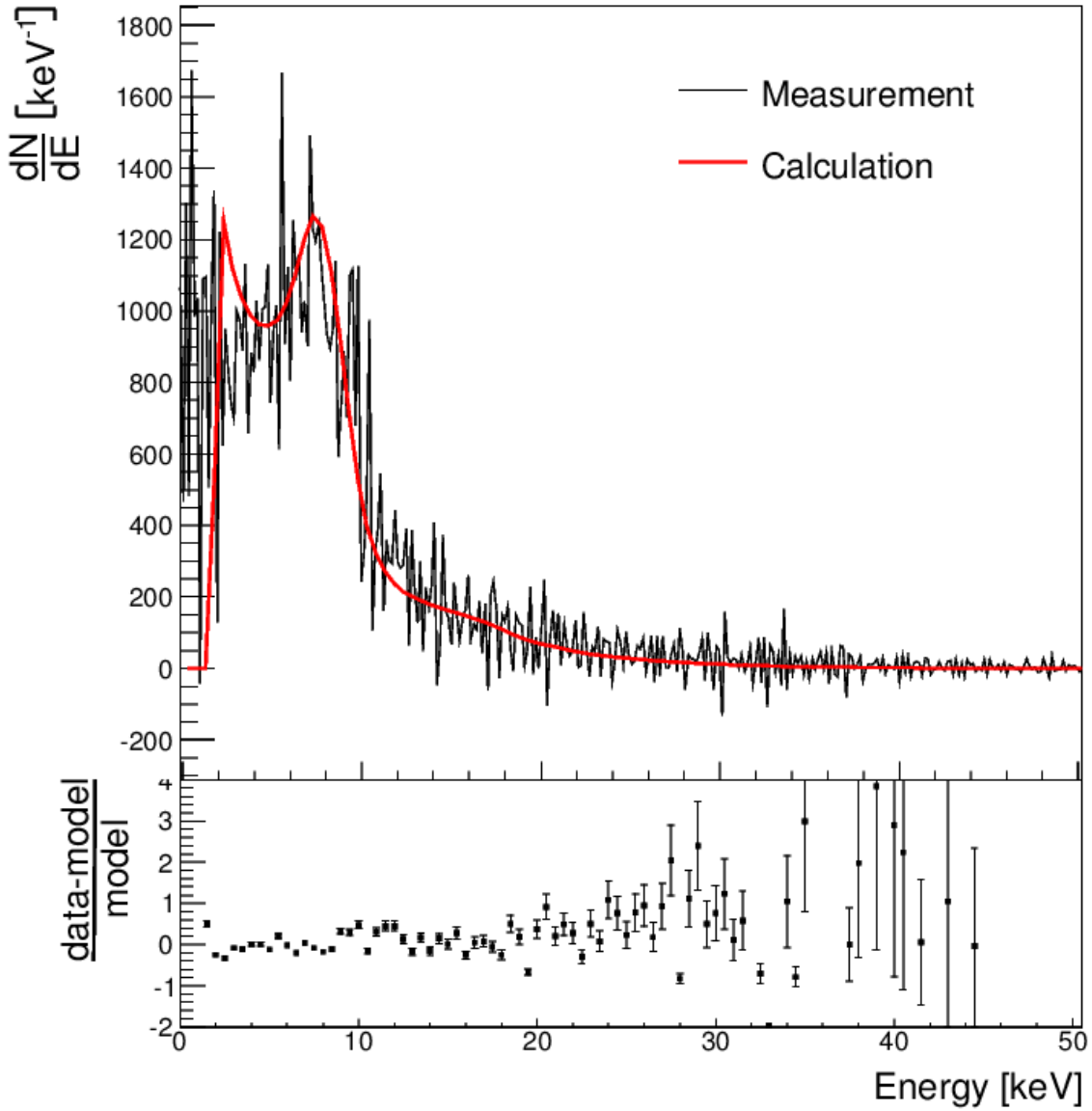


$$N_{l,\theta,t} = \int_t^{+\infty} \ldots \boxed{R(E,E')} \ldots e^{-\int_{l,\theta} \sum_m^M \mu_m(s,E)\,ds}$$

Calculate detector spectra for any given input spectrum



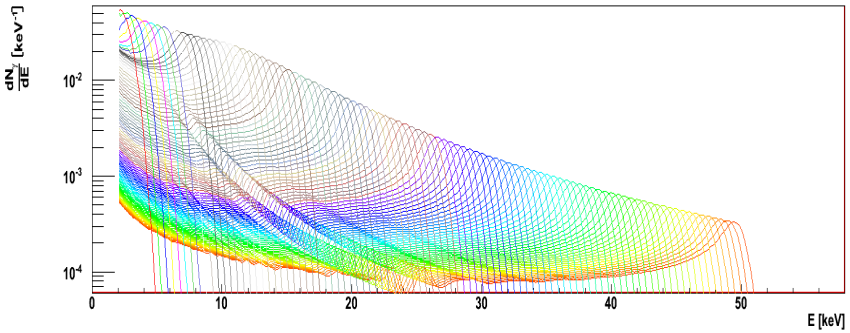
Whatever input spectrum



Detector spectrum

How to improve the response function?

```
if(chargeSharing){
   R(E,E')=
```




```
;
}
else{
   R(E,E')= Gauss(E,sigma);
```

$$\text{Conv}\left(\int_0^{+\infty} dE\, R(E;E')\, I_0(E)\, e^{-\int_{l,\theta} \mu(s,E)\, ds}\right);$$

```
}
```

Medipix3 ...

How to really solve CT?

$$N_{l,\theta,t} = \int_t^{+\infty} \ldots R(E, E') \ldots e^{-\int_{l,\theta} \sum_m^M \alpha_m \mu_m(s,E)\, ds}$$

1 - the threshold trick

2 - the detector response

3 – how do we invert the integral?

How to really solve CT?

$$N_{l,\theta,t} = \int_t^{+\infty} \ldots R(E, E') \ldots e^{-\int_{l,\theta} \sum_m^M \alpha_m \mu_m(s,E)\, ds}$$

1 - the threshold trick

2 - the detector response

3 – how do we invert the integral?

Spectral computed tomography

simulation studies

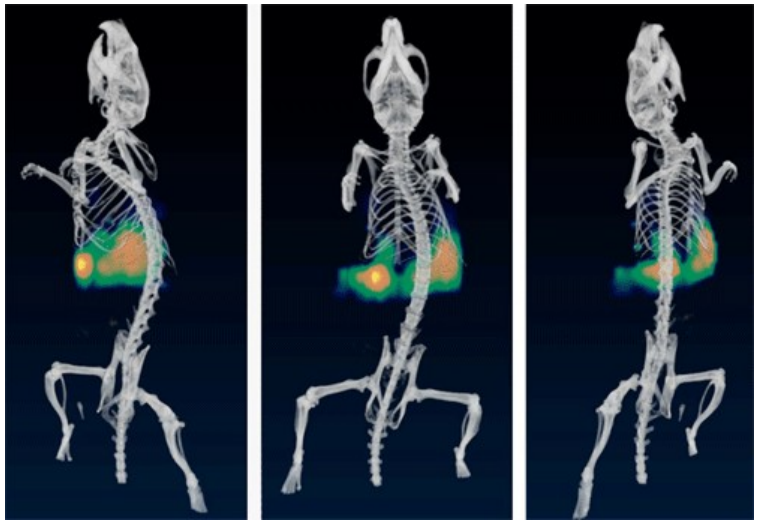
Motivation

- Artifact free
- Material decomposition

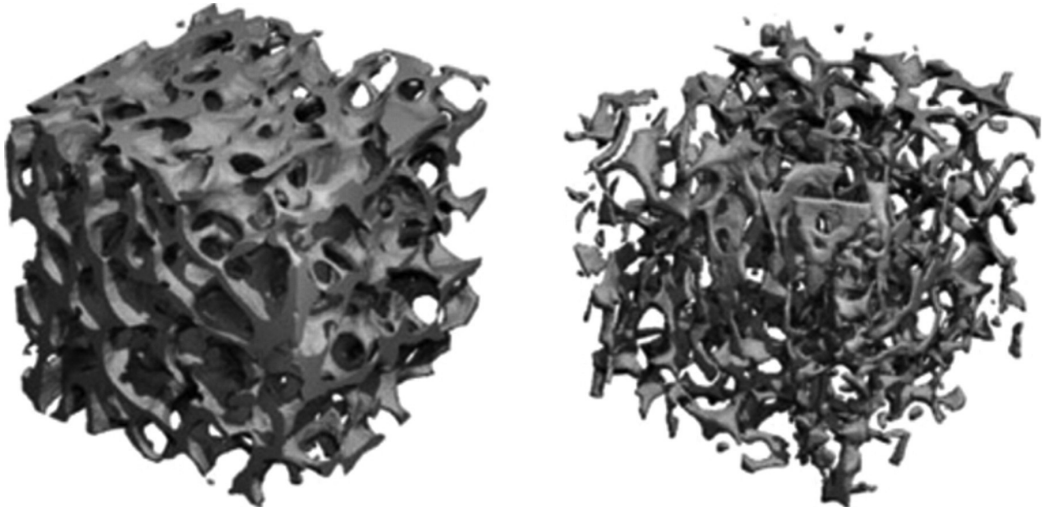
State of the art

- Spectroscopic pixel detectors appeared only recently
- Big companies do not disclose their progress!

Many, MANY, applications!

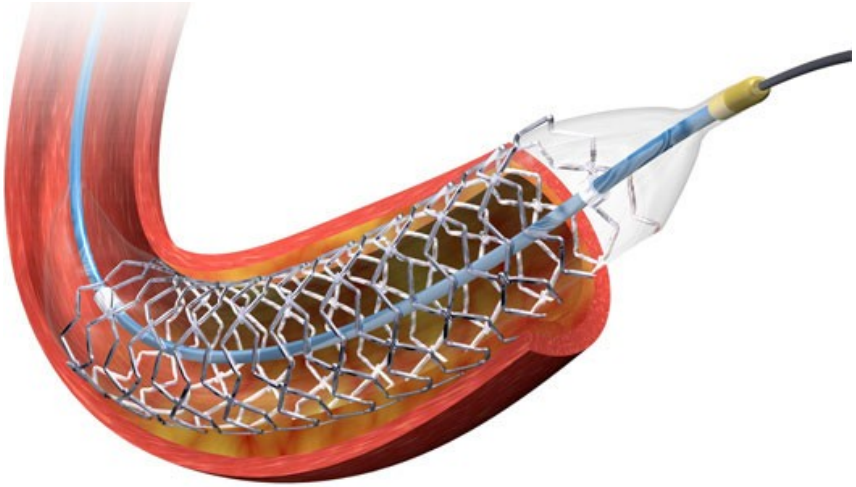


Functional CT



micro CT (e.g. bone tissue)

Industrial metrology



Medical CT

Inversion problem, approach #1: **iterative**

$$\boxed{N_{l,\theta,t}} = \int_t^{+\infty} dE' \int_0^{+\infty} dE\, R(E;E')\, I_0(E)\, e^{-\int_{l,\theta} \sum_m^M \boxed{\alpha_m} \mu_m(s,E)\, ds}$$

coefficients

unknowns

Inversion problem, approach #1: **iterative**

$$\boxed{N_{l,\theta,t}} = \int_t^{+\infty} dE' \int_0^{+\infty} dE\, R(E;E')\, I_0(E)\, e^{-\int_{l,\theta} \sum_m^M \boxed{\alpha_m} \mu_m(s,E)\, ds}$$

coefficients

unknowns

1 – initial guess: α_m^0

Inversion problem, approach #1: **iterative**

$$\boxed{N_{l,\theta,t}} = \int_t^{+\infty} dE' \int_0^{+\infty} dE\, R(E;E')\, I_0(E)\, e^{-\int_{l,\theta} \sum_m^M \boxed{\alpha_m} \mu_m(s,E)\, ds}$$

coefficients

unknowns

1 – initial guess: α_m^0

2 – compute image: $N_{l,\theta,t}^0$

Inversion problem, approach #1: **iterative**

$$\boxed{N_{l,\theta,t}} = \int_t^{+\infty} dE' \int_0^{+\infty} dE\, R(E;E')\, I_0(E)\, e^{-\int_{l,\theta} \sum_m^M \boxed{\alpha_m} \mu_m(s,E)\, ds}$$

coefficients

unknowns

1 – initial guess: α_m^0

2 – compute image: $N_{l,\theta,t}^0$

3 – compare: $N_{l,\theta,t}^0 \; vs \; N_{l,\theta,t}$

Inversion problem, approach #1: **iterative**

$$\boxed{N_{l,\theta,t}} = \int_t^{+\infty} dE' \int_0^{+\infty} dE\, R(E;E')\, I_0(E)\, e^{-\int_{l,\theta} \sum_m^M \boxed{\alpha_m} \mu_m(s,E)\, ds}$$

coefficients

unknowns

1 – initial guess: α_m^0

2 – compute image: $N_{l,\theta,t}^0$

3 – compare: $N_{l,\theta,t}^0 \; vs \; N_{l,\theta,t}$

4 – corrections: $\epsilon_{l,\theta,t}^0$

Inversion problem, approach #1: **iterative**

$$\boxed{N_{l,\theta,t}} = \int_t^{+\infty} dE' \int_0^{+\infty} dE\, R(E;E')\, I_0(E)\, e^{-\int_{l,\theta} \sum_m^M \boxed{\alpha_m} \mu_m(s,E)\, ds}$$

coefficients

unknowns

1 – initial guess: α_m^0

2 – compute image: $N_{l,\theta,t}^0$

3 – compare: $N_{l,\theta,t}^0 \; vs \; N_{l,\theta,t}$

4 – corrections: $\epsilon_{l,\theta,t}^0$

5 – update guess: α_m^1

Inversion problem, approach #1: **iterative**

$$\boxed{N_{l,\theta,t}} = \int_t^{+\infty} dE' \int_0^{+\infty} dE\, R(E;E')\, I_0(E)\, e^{-\int_{l,\theta} \sum_m^M \boxed{\alpha_m} \mu_m(s,E)\, ds}$$

coefficients

unknowns

1 – initial guess: α_m^0

2 – compute image: $N_{l,\theta,t}^0$

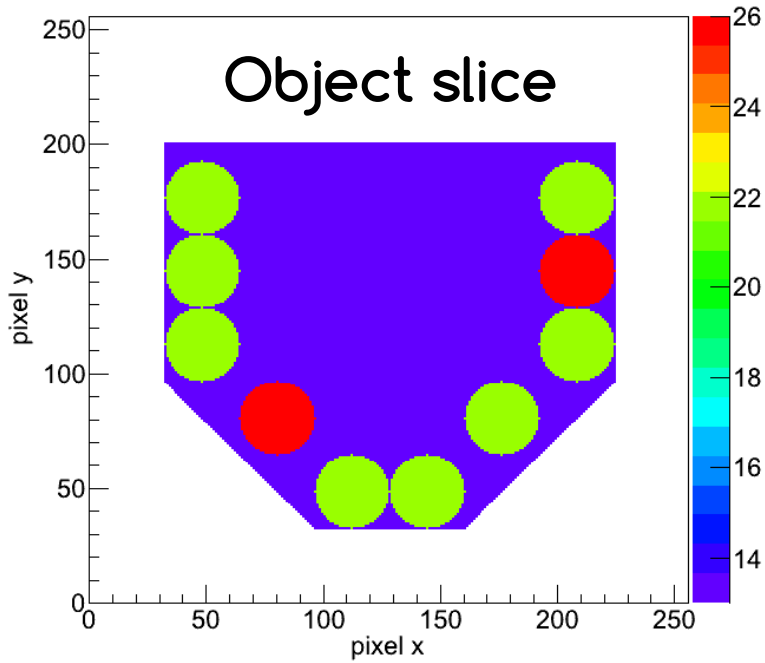
3 – compare: $N_{l,\theta,t}^0 \; vs \; N_{l,\theta,t}$

4 – corrections: $\epsilon_{l,\theta,t}^0$

5 – update guess: α_m^1

Iterate until convergence

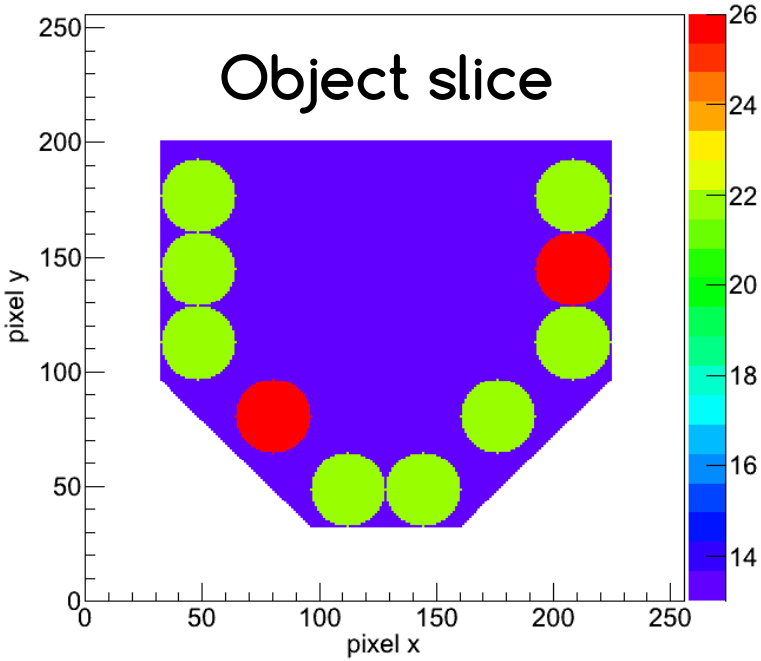
A simulation study



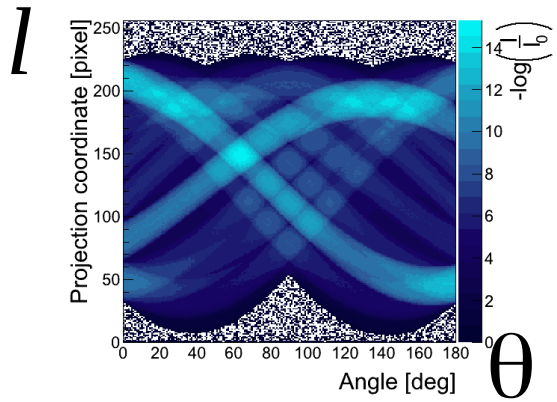
Blue = Al
Green = Ti
Red = Fe

α_m (truth)

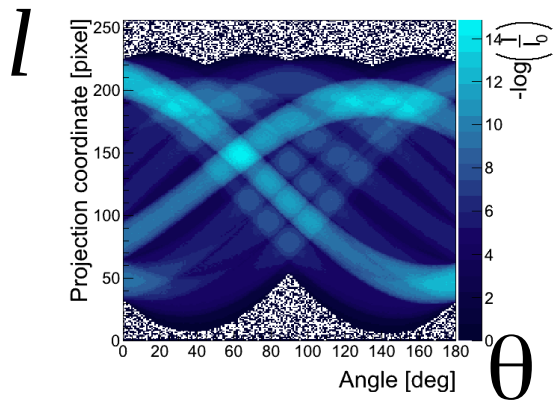
A simulation study



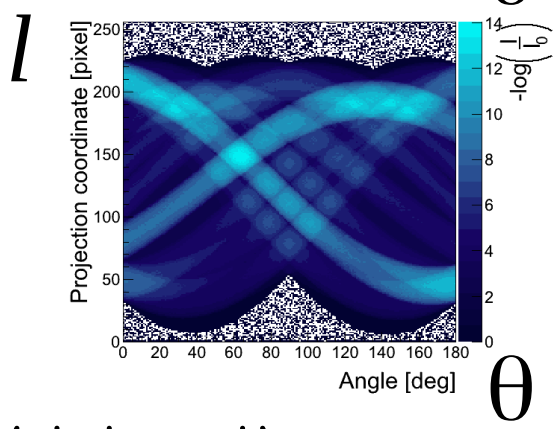
Threshold
3 keV



Threshold
10 keV



Threshold
20 keV

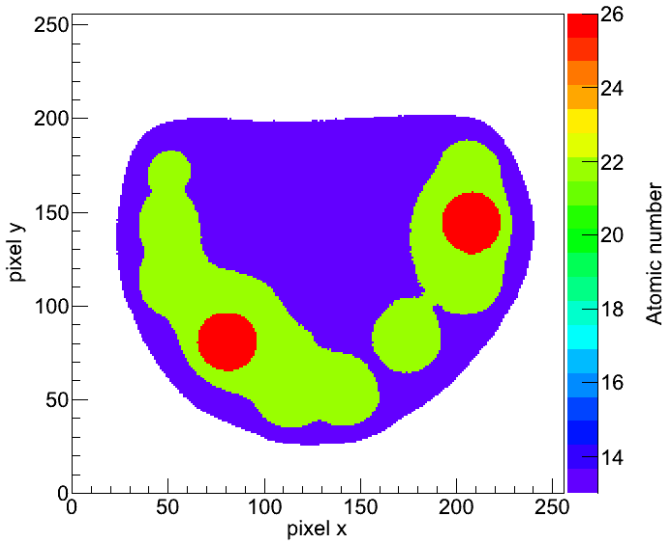


Blue = Al
Green = Ti
Red = Fe

α_m (truth)

$N_{l,\theta,t}$ (dataset)

A simulation study



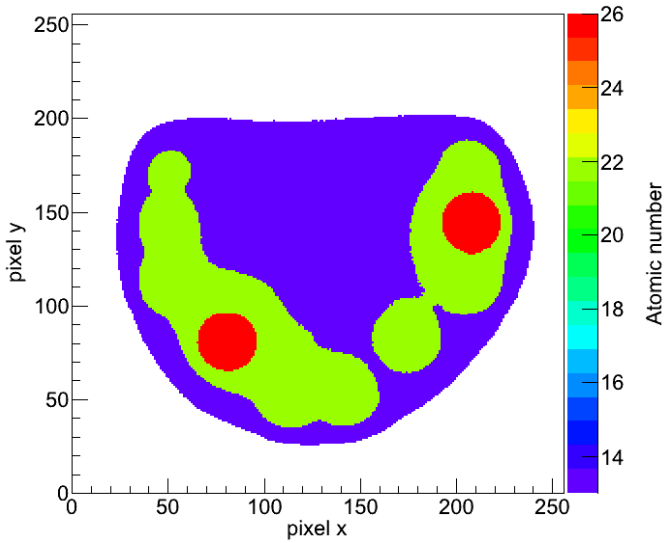
Blue = Al

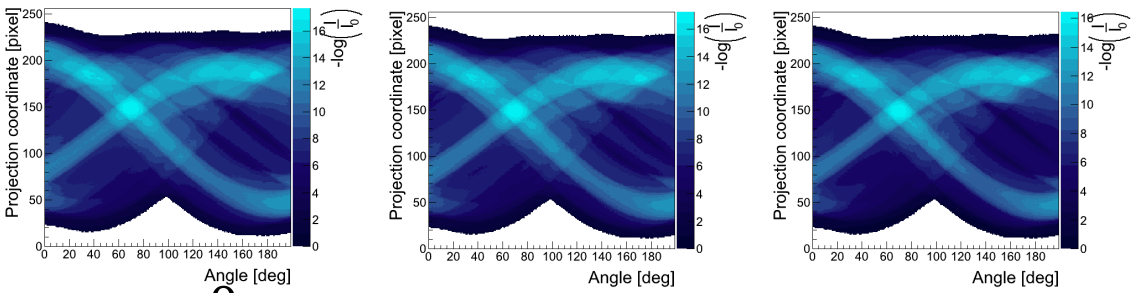
Green = Ti

Red = Fe

α_m^0 (initial guess)

A simulation study





$N^0_{l,\theta,t}$ (computed dataset)

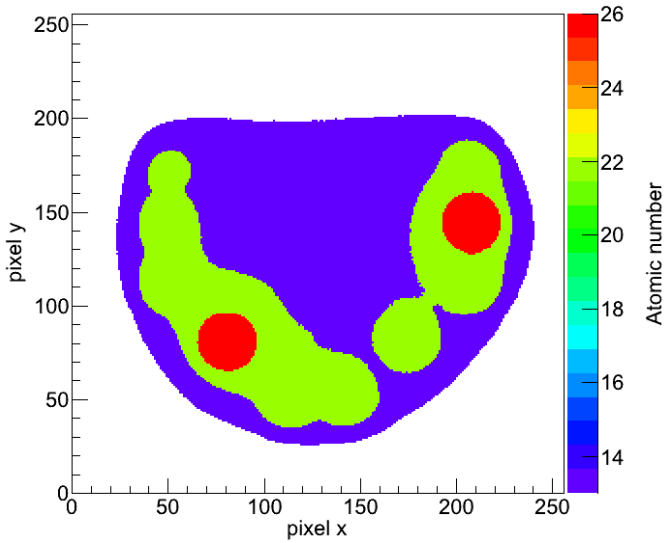
Blue = Al

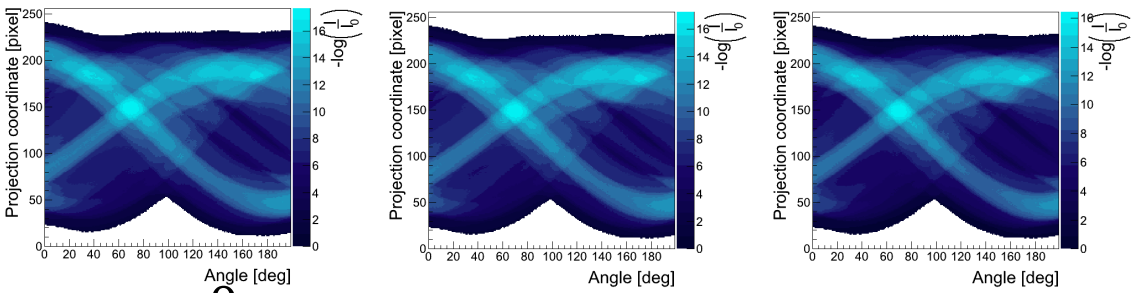
Green = Ti

Red = Fe

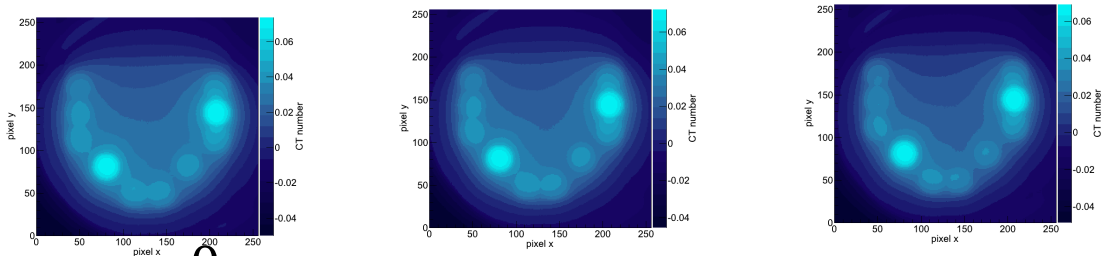
α^0_m (initial guess)

A simulation study





$N^0_{l,\theta,t}$ (computed dataset)



$\epsilon^0_{l,\theta,t}$ (correction factors)

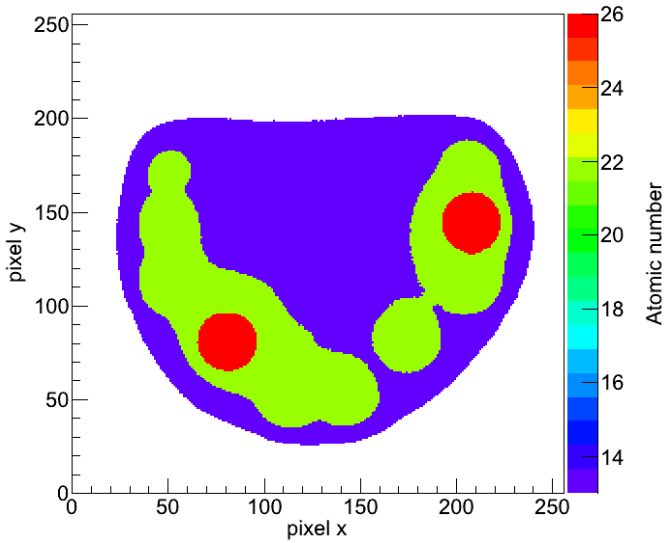
Blue = Al

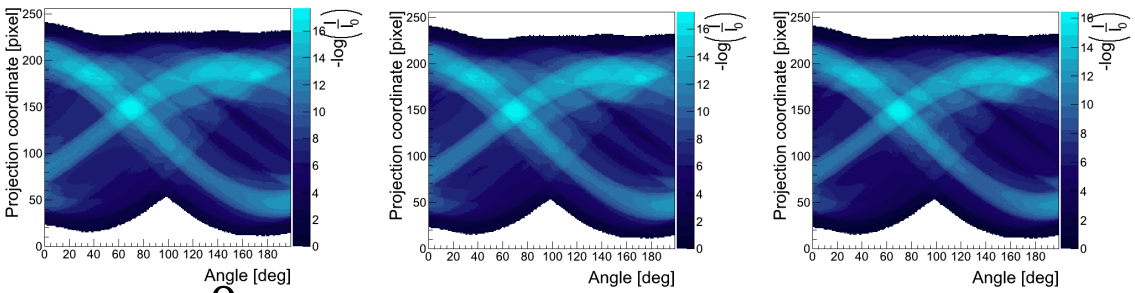
Green = Ti

Red = Fe

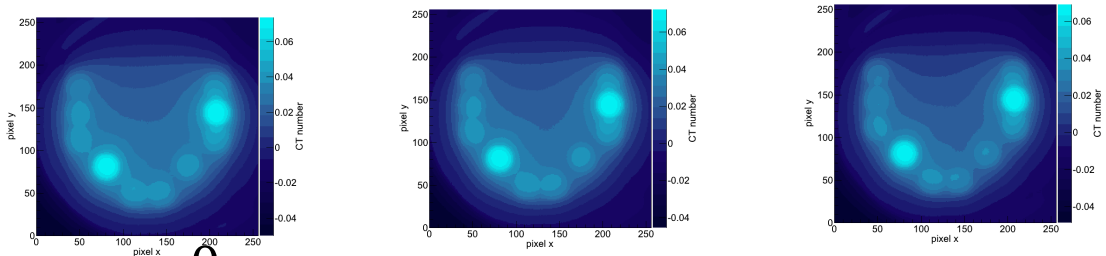
α^0_m (initial guess)

A simulation study





$N^0_{l,\theta,t}$ (computed dataset)



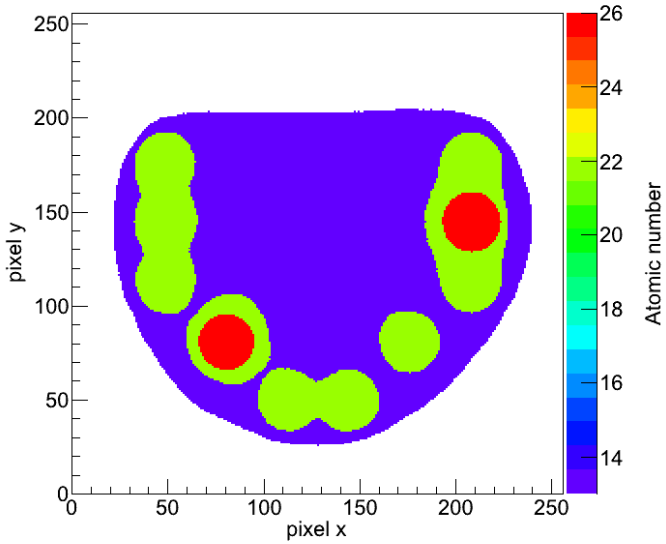
$\epsilon^0_{l,\theta,t}$ (correction factors)

Blue = Al

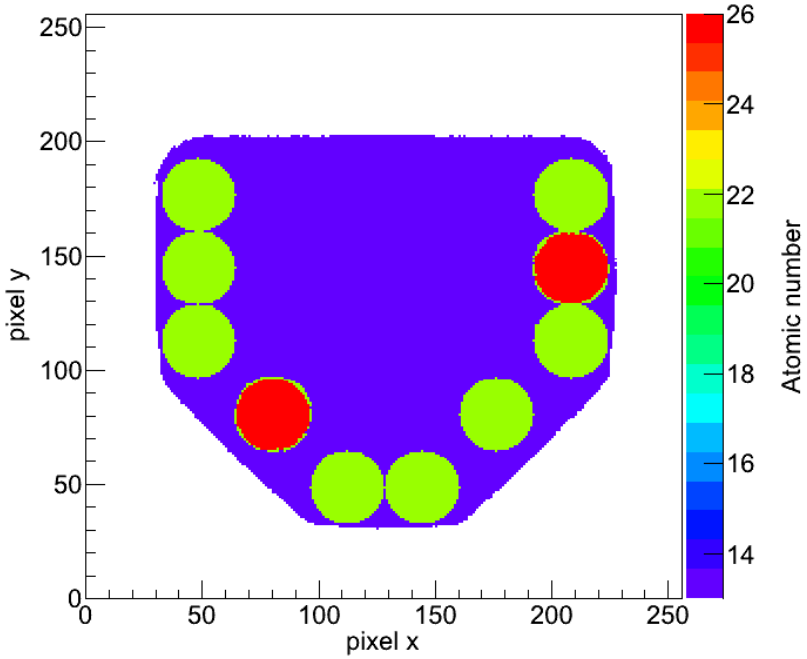
Green = Ti

Red = Fe

α^0_m (initial guess)



α^1_m

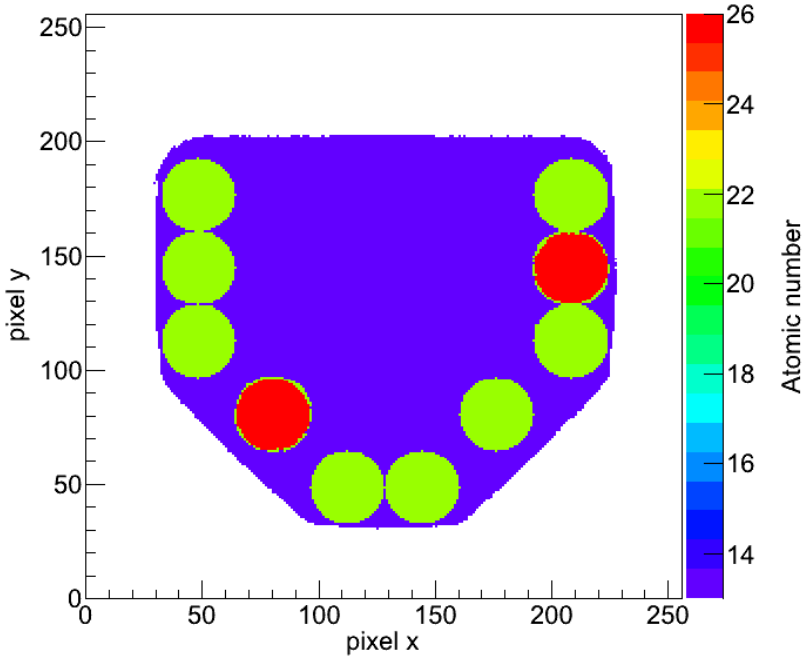


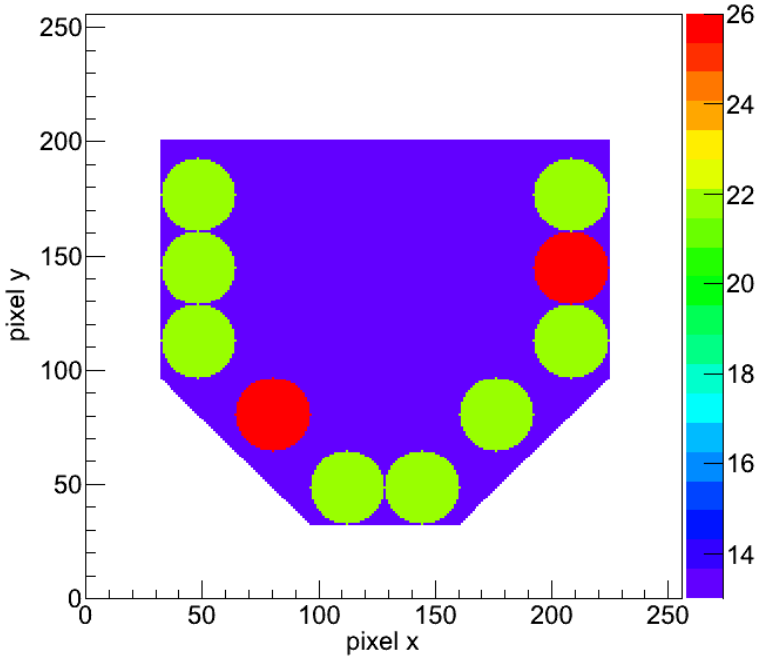
Blue = Al

Green = Ti

Red = Fe

$$\alpha_m^N$$



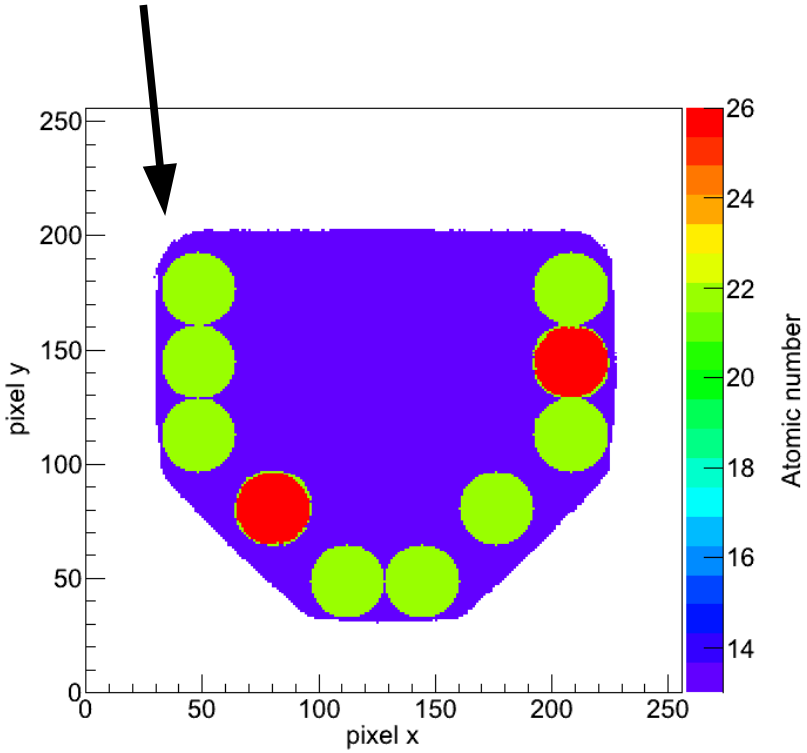


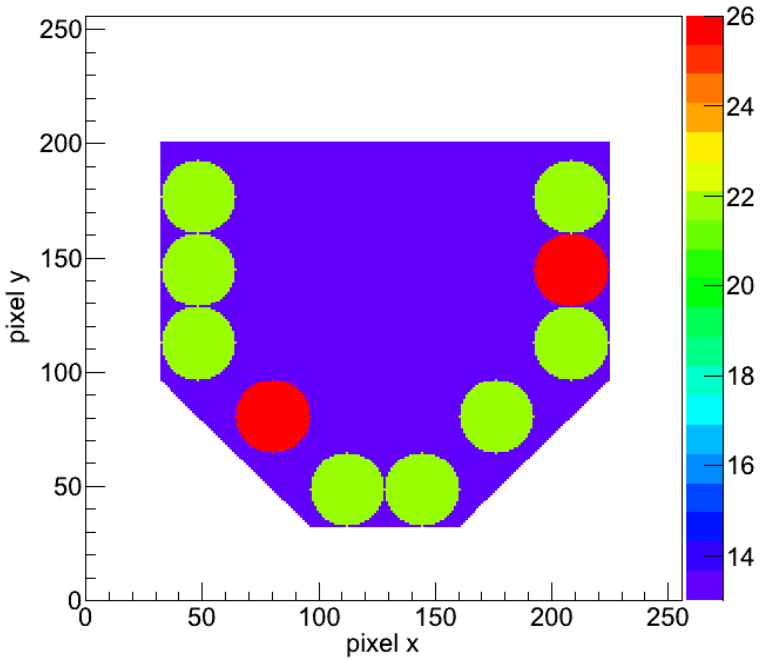
Blue = Al
Green = Ti
Red = Fe

α_m^N

Blue = Al
Green = Ti
Red = Fe

α_m (truth)



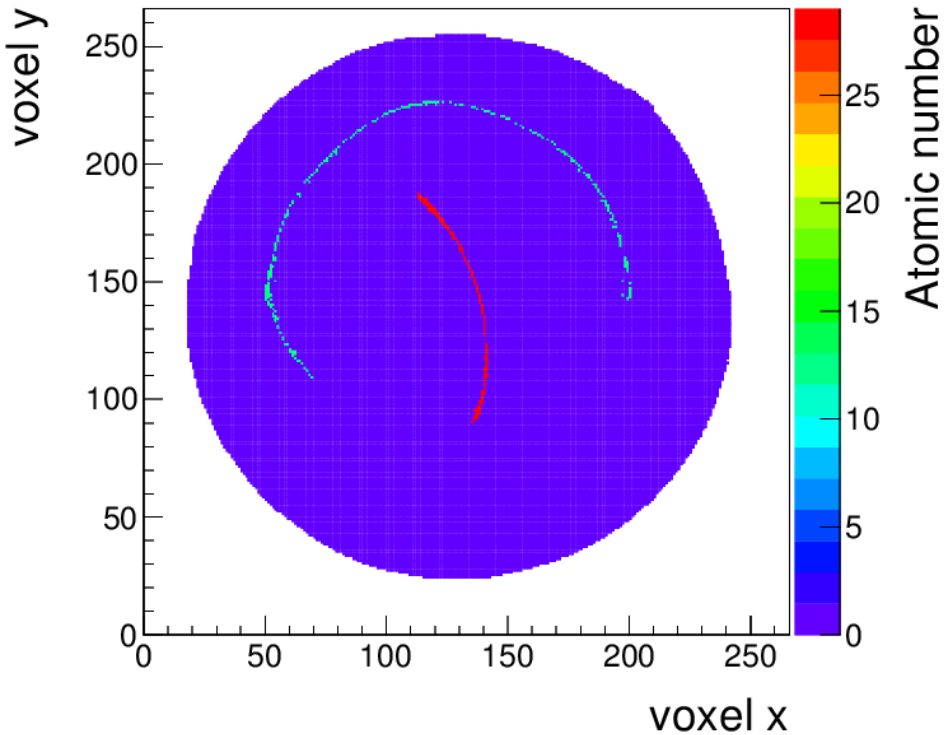


Blue = Al
Green = Ti
Red = Fe

α_m^N

Blue = Al
Green = Ti
Red = Fe

α_m (truth)

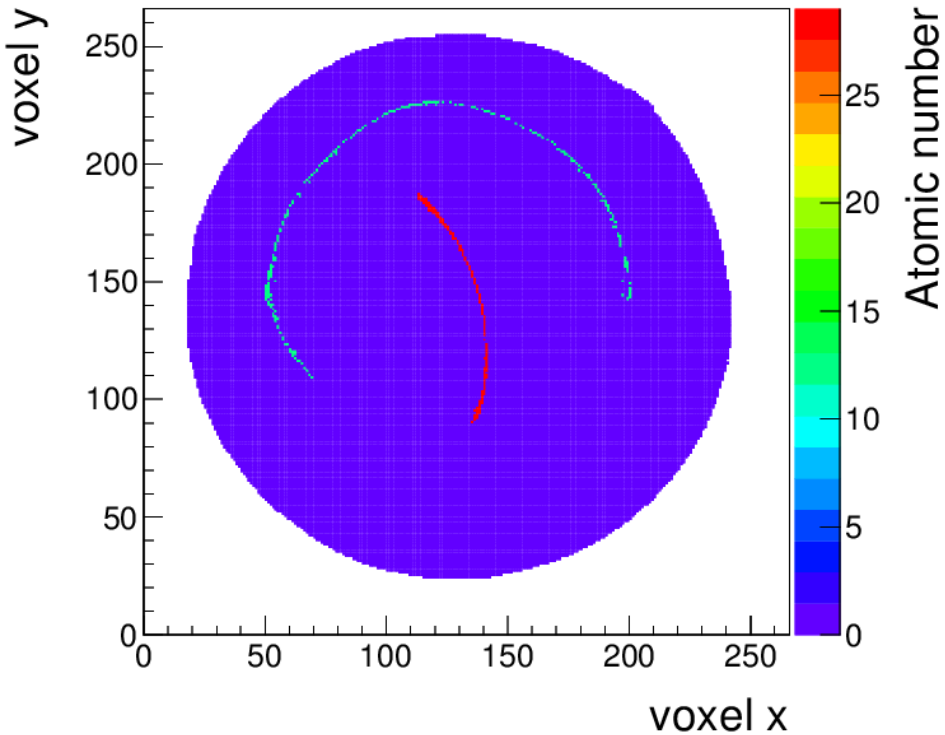


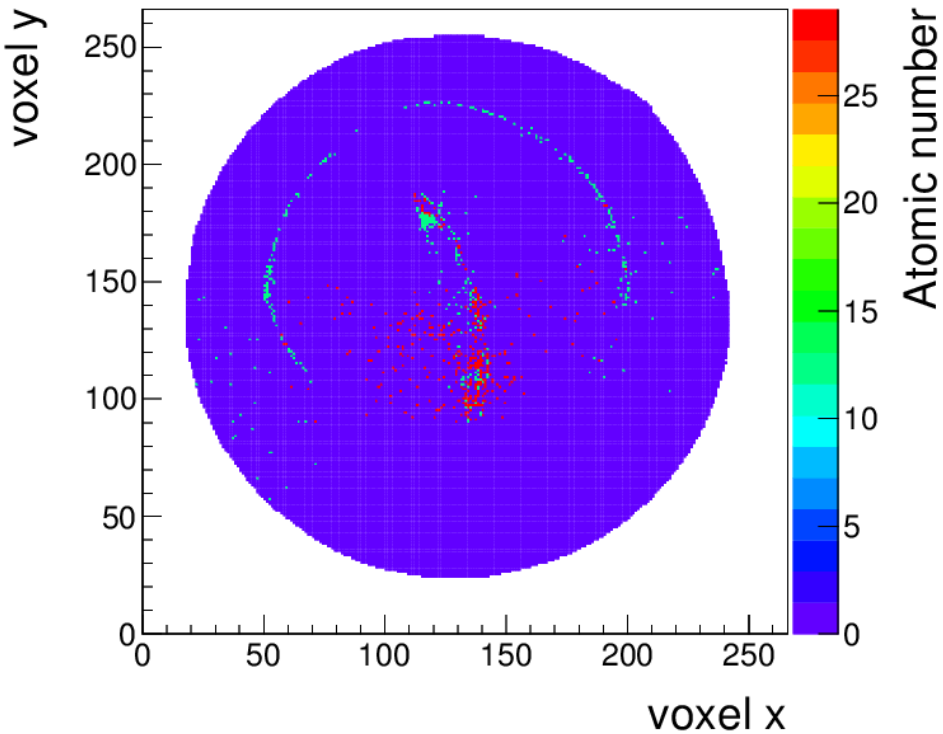
Blue = wax

Green = Al

Red = Cu

α_m (truth)





Blue = wax
Green = Al
Red = Cu

α_m (truth)

- Divergence after few iterations
- Material space decoupled from coordinates space

Inversion problem, approach #1: **statistical**

$$\boxed{N_{l,\theta,t}} = \int_t^{+\infty} dE' \int_0^{+\infty} dE\, R(E;E')\, I_0(E)\, e^{-\int_{l,\theta} \sum_m^M \boxed{\alpha_m} \mu_m(s,E)\, ds}$$

coefficients

unknowns

Inversion problem, approach #1: **statistical**

$$\boxed{N_{l,\theta,t}} = \int_t^{+\infty} dE' \int_0^{+\infty} dE\, R(E;E')\, I_0(E)\, e^{-\int_{l,\theta} \sum_m^M \boxed{\alpha_m} \mu_m(s,E)\, ds}$$

coefficients

unknowns

Number of photons

Inversion problem, approach #1: **statistical**

$$\boxed{N_{l,\theta,t}} = \int_t^{+\infty} dE' \int_0^{+\infty} dE\, R(E;E')\, I_0(E)\, e^{-\int_{l,\theta} \sum_m^M \boxed{\alpha_m} \mu_m(s,E)\, ds}$$

coefficients

unknowns

Number of photons → Poisson statistics

Inversion problem, approach #1: **statistical**

$$\boxed{N_{l,\theta,t}} = \int_t^{+\infty} dE' \int_0^{+\infty} dE\, R(E;E')\, I_0(E)\, e^{-\int_{l,\theta} \sum_m^M \boxed{\alpha_m} \mu_m(s,E)\, ds}$$

coefficients

unknowns

Number of photons → Poisson statistics

$$P(X_{l,\theta,t} | N_{l,\theta,t}) = \frac{N_{l,\theta,t}^{X_{l,\theta,t}} e^{-N_{l,\theta,t}}}{X_{l,\theta,t}!}$$

Assumption: independent variables

$$P\left(X_{l,\theta,t} \middle| N_{l,\theta,t}\right) = \frac{N_{l,\theta,t}^{X_{l,\theta,t}} e^{-N_{l,\theta,t}}}{X_{l,\theta,t}!}$$

Assumption: independent variables

$$P\left(X_{l,\theta,t} \middle| N_{l,\theta,t}\right) = \frac{N_{l,\theta,t}^{X_{l,\theta,t}} e^{-N_{l,\theta,t}}}{X_{l,\theta,t}!}$$

$$P\left(X \middle| N\right) = \prod_{l} \prod_{\theta} \prod_{t} \frac{N_{l,\theta,t}^{X_{l,\theta,t}} e^{-N_{l,\theta,t}}}{X_{l,\theta,t}!}$$

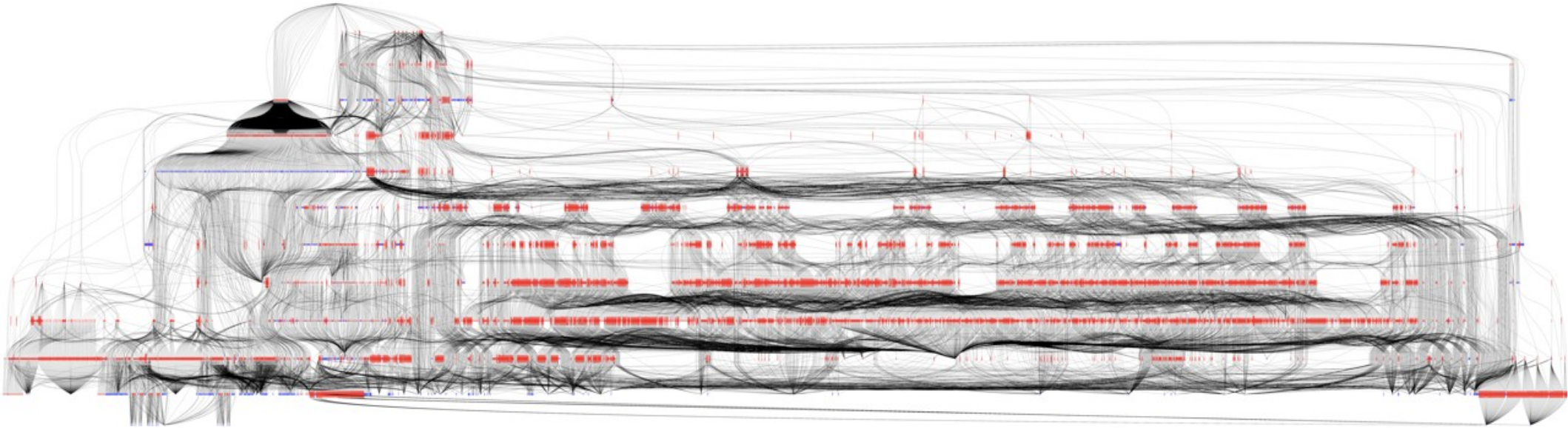
Assumption: independent variables

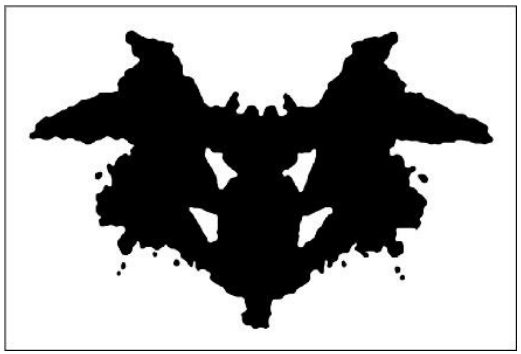
$$P(X_{l,\theta,t}|N_{l,\theta,t}) = \frac{N_{l,\theta,t}^{X_{l,\theta,t}} e^{-N_{l,\theta,t}}}{X_{l,\theta,t}!}$$

$$P(X|N) = \prod_{l} \prod_{\theta} \prod_{t} \frac{N_{l,\theta,t}^{X_{l,\theta,t}} e^{-N_{l,\theta,t}}}{X_{l,\theta,t}!}$$

Image ↔ maximum likelihood

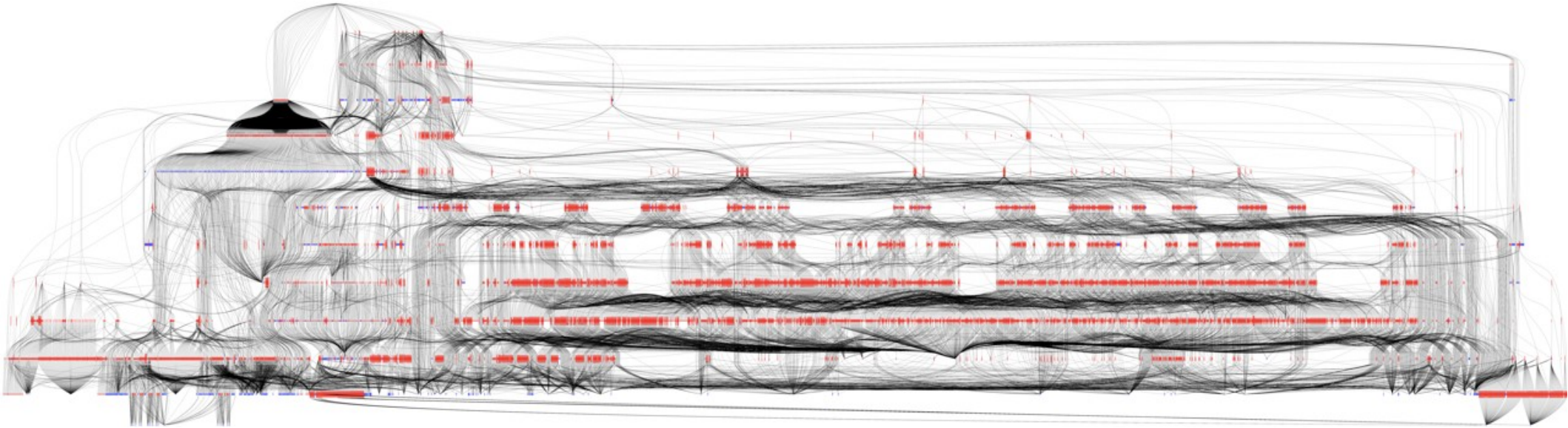
Particle physicists are good at maximizing functions...





What do you see?

Particle physicists are good at maximizing functions...



The full Higgs combination model, 23000 functions, 1600 parameters
Image credit http://cds.nyu.edu/projects/collaborative-statistical-modeling/

... but how big is our function?

$$N_{l,\theta,t} = 54k$$

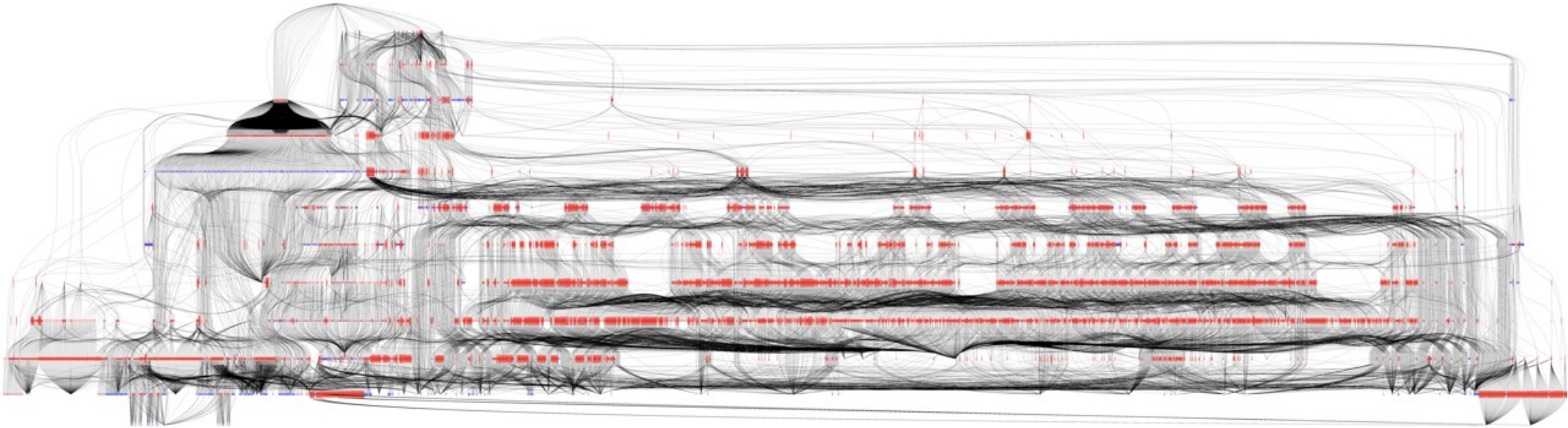
100 180 3

$$N_{voxels} = 100 \times 100 = 10\text{k}$$

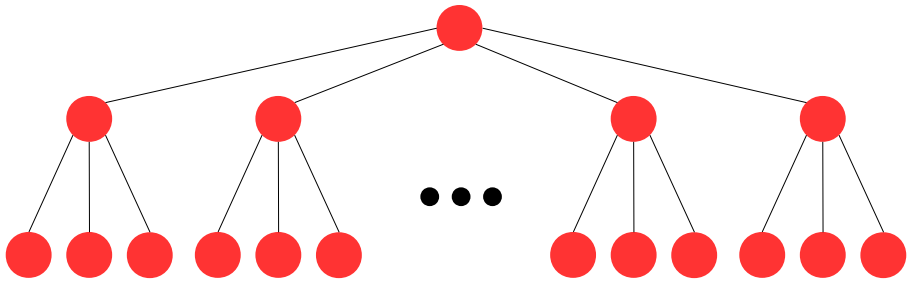
$$N_{materials} = 3$$

$$dim(Img) = 30\text{k}$$

Particle physics vs CT likelihood



Particle physics: complex model, “few” parameters



CT: simple model, many parameters

Developing RooFit for CT at Nikhef

Nikhef
Science Park
Amsterdam
The Netherlands

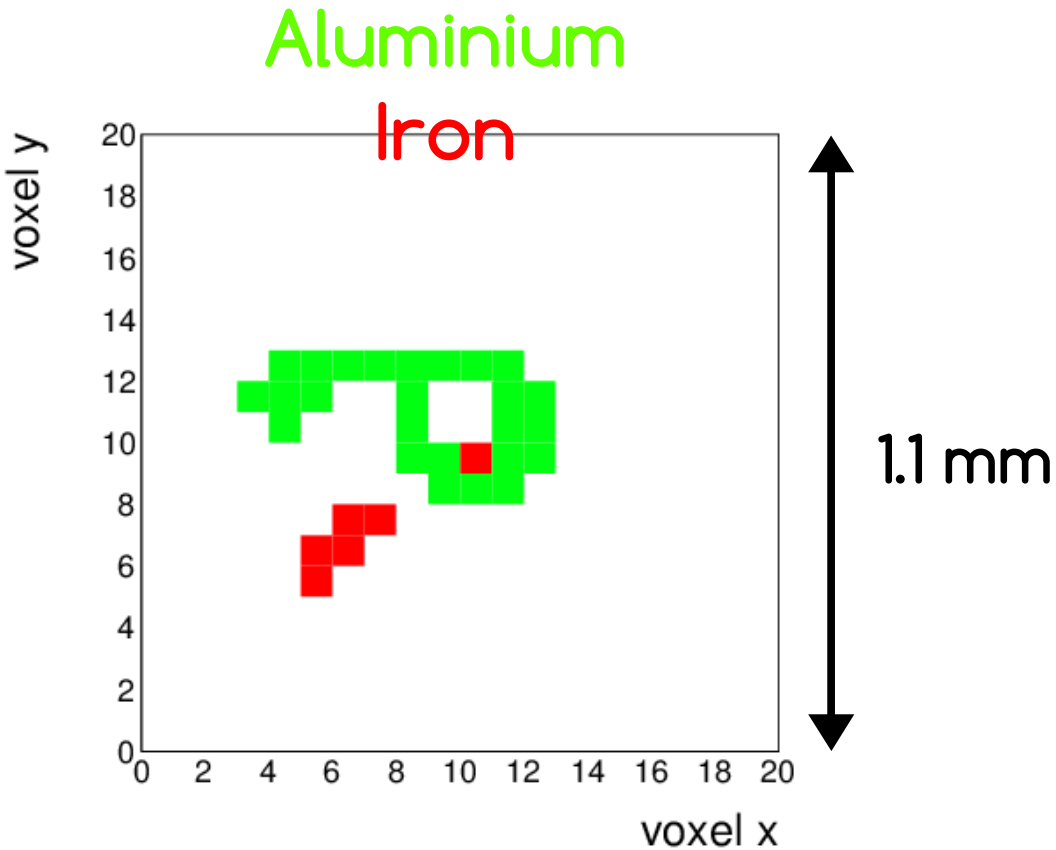
W. Verkerke →

me →

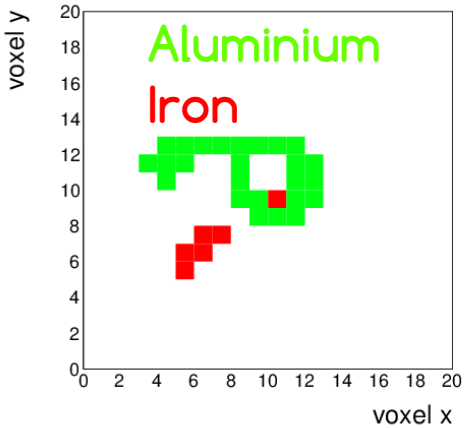
A RooFit simulation study

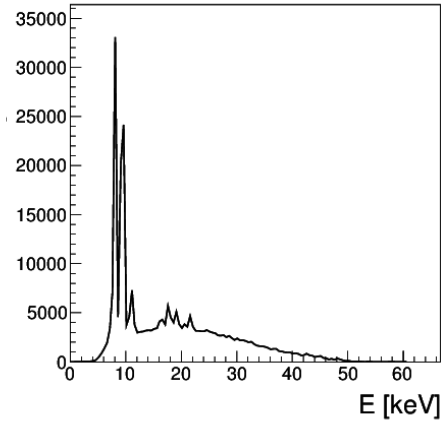
- Compiling dedicated Root version
- Running on dedicated machine in the Nikhef cluster (Stoomboot)
  - 8 cores
  - 16 Gb RAM

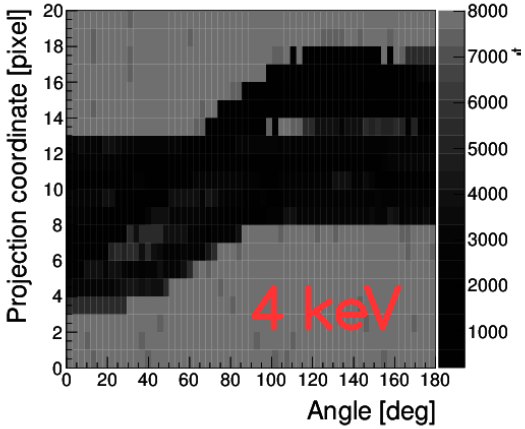
  → $\mathcal{O}$(1 day) to simulate a 20 x 20 image

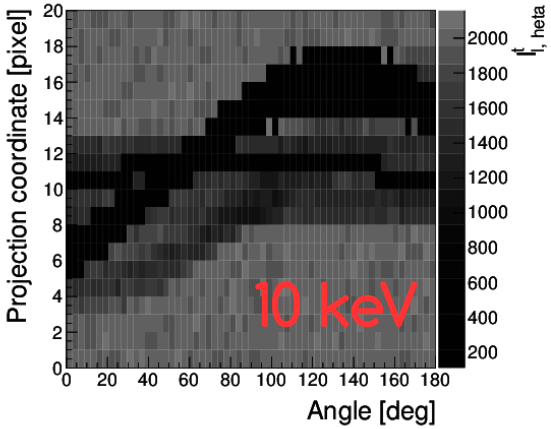


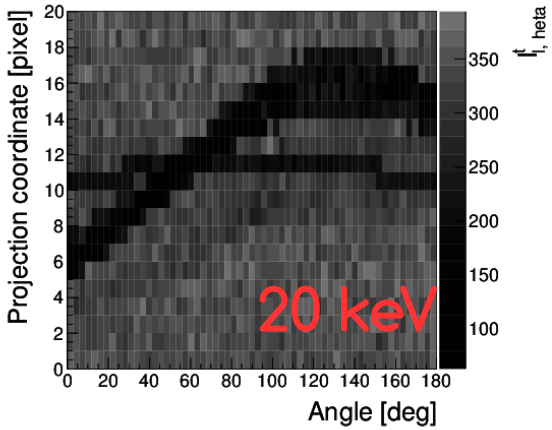
A RooFit simulation study



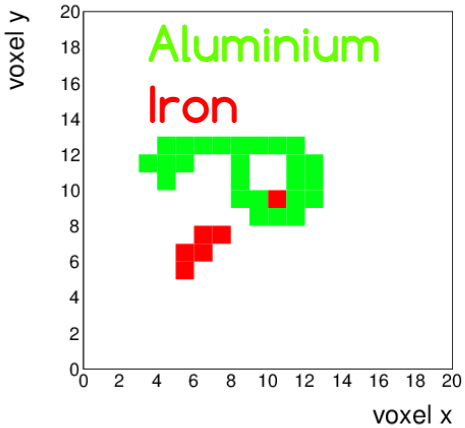


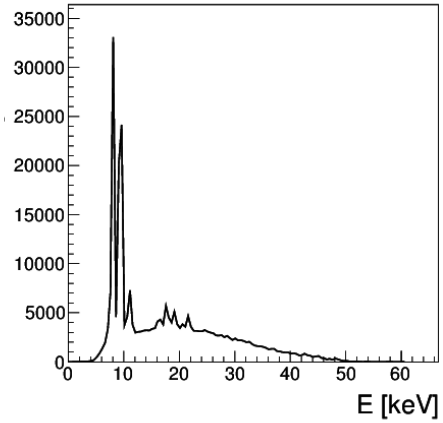


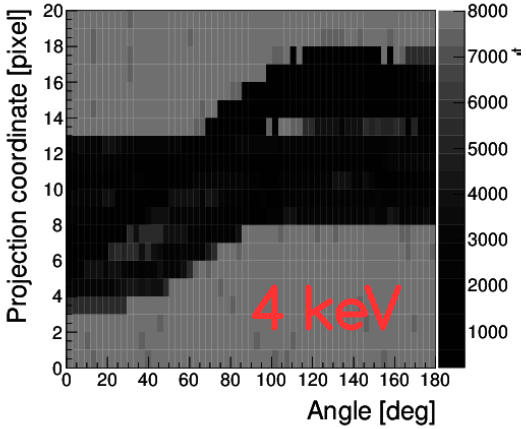


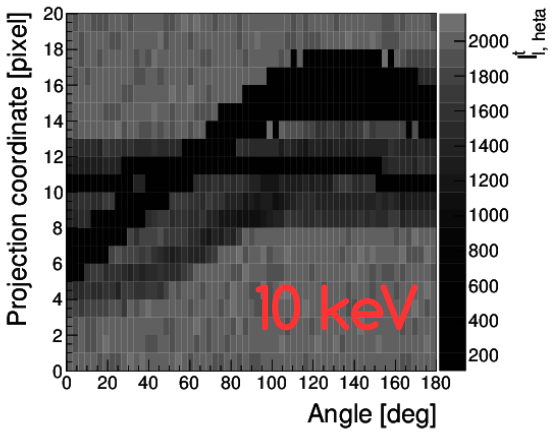


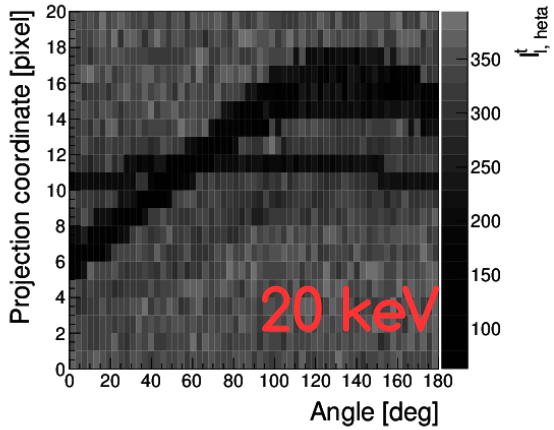
A RooFit simulation study

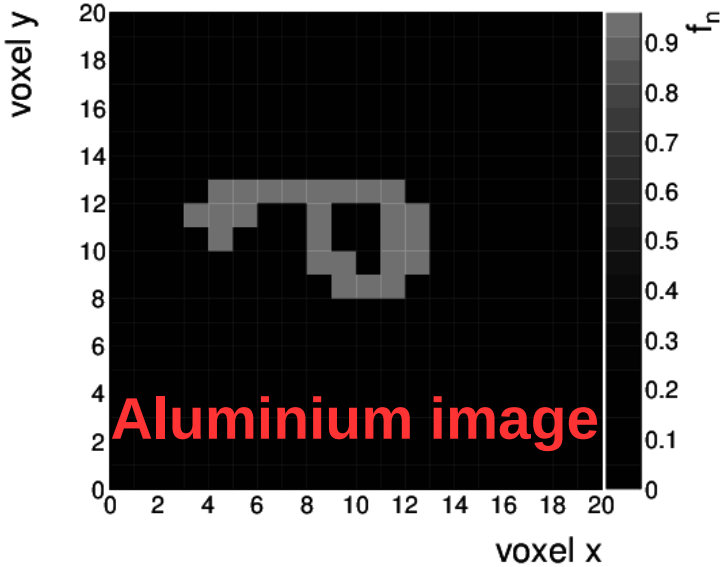


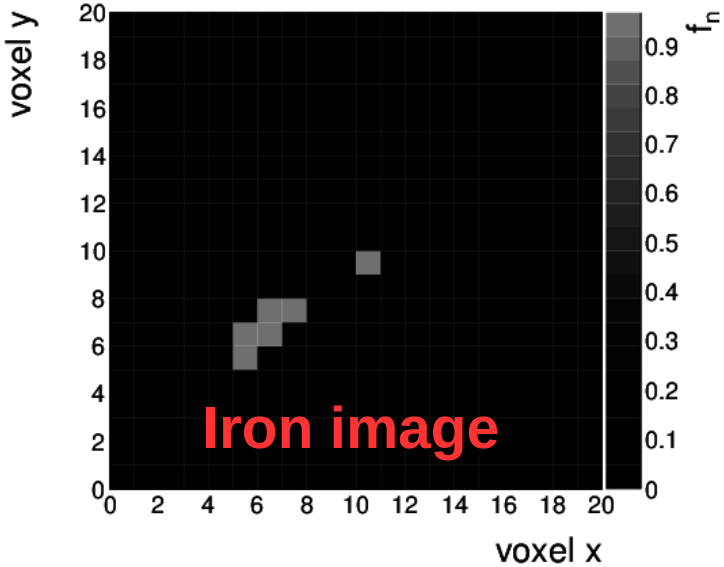




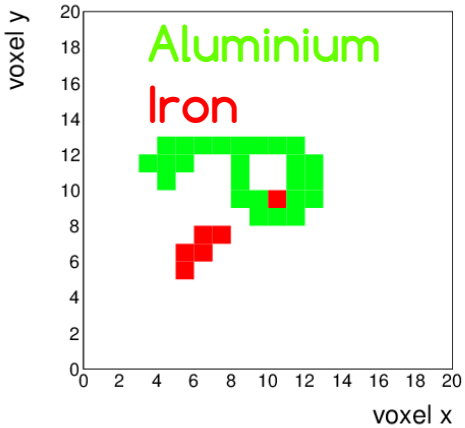


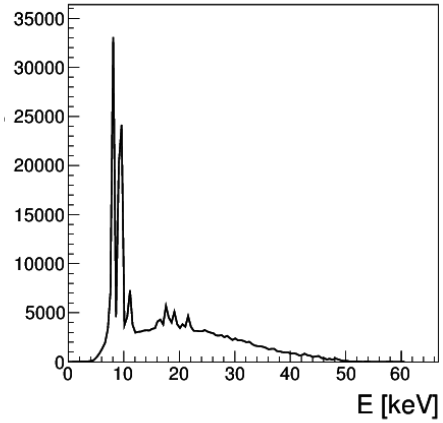


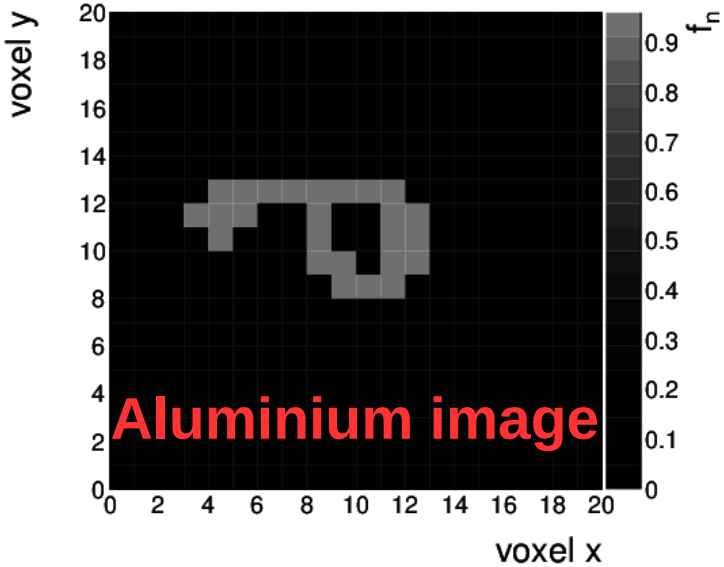


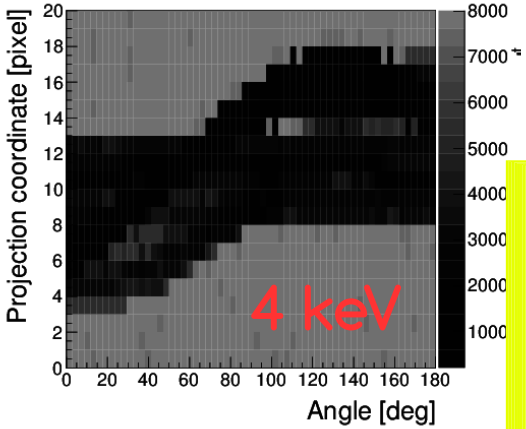


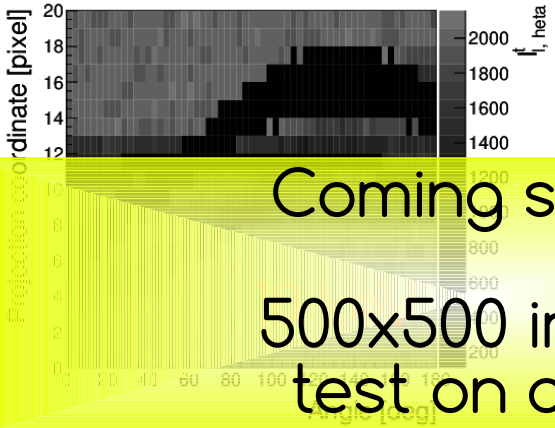
A RooFit simulation study





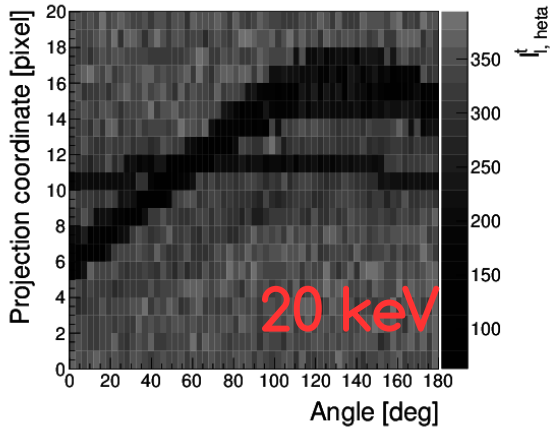


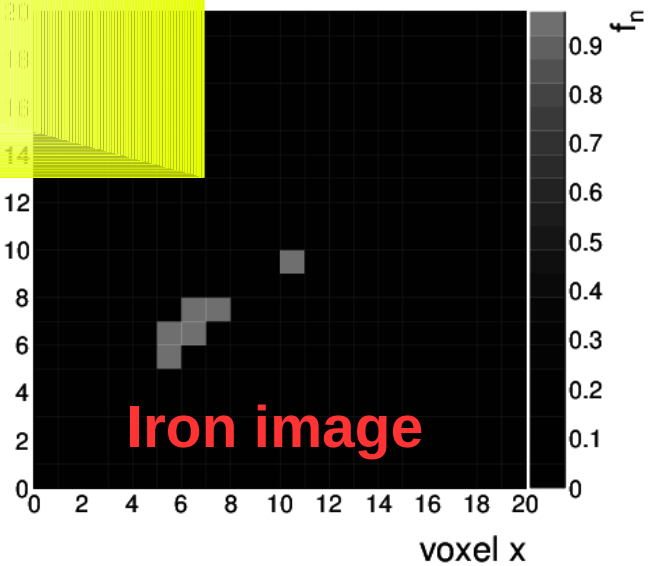




Coming soon:

500x500 image
test on data





How to really solve CT?

$$N_{l,\theta,t} = \int_{t}^{+\infty} \ldots R(E, E') \ldots e^{-\int_{l,\theta} \sum_{m}^{M} \alpha_m \mu_m(s, E)\, ds}$$

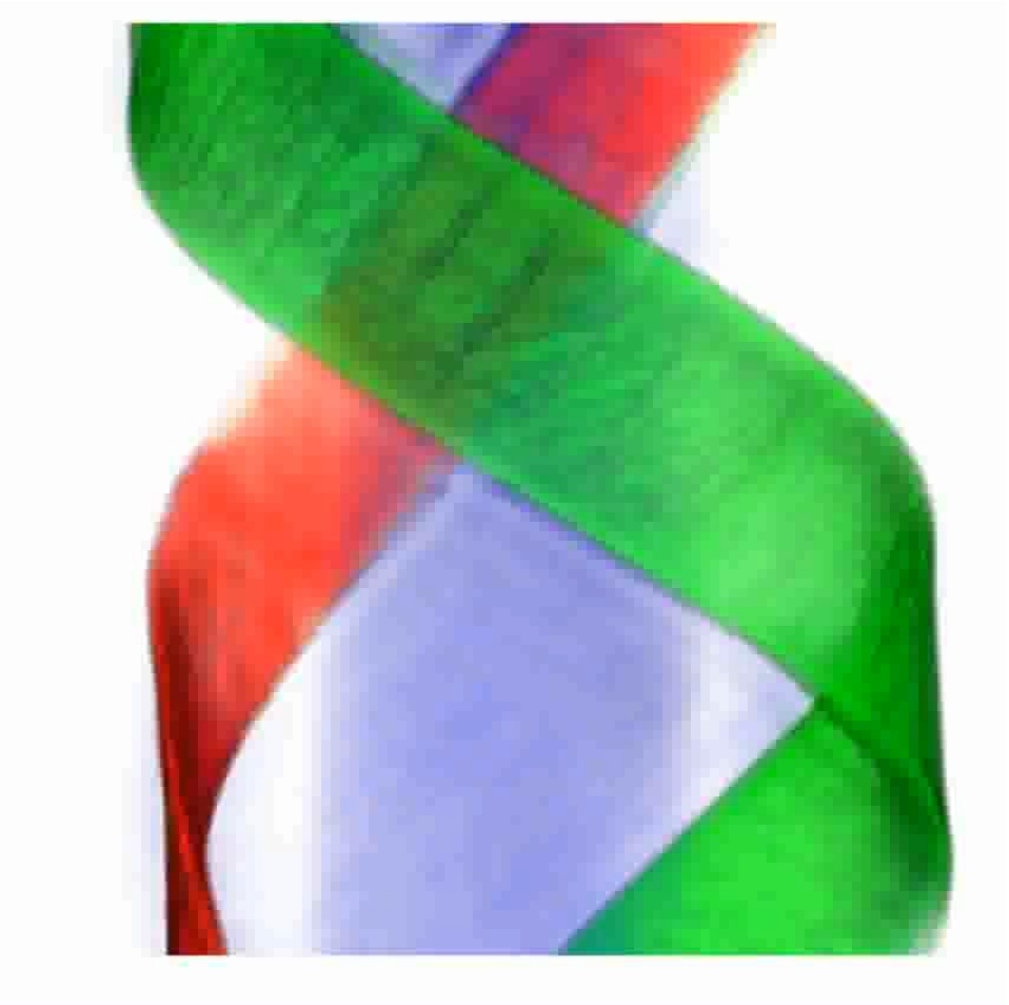
1 - the threshold trick

2 - the detector response

3 – how do we invert the integral?

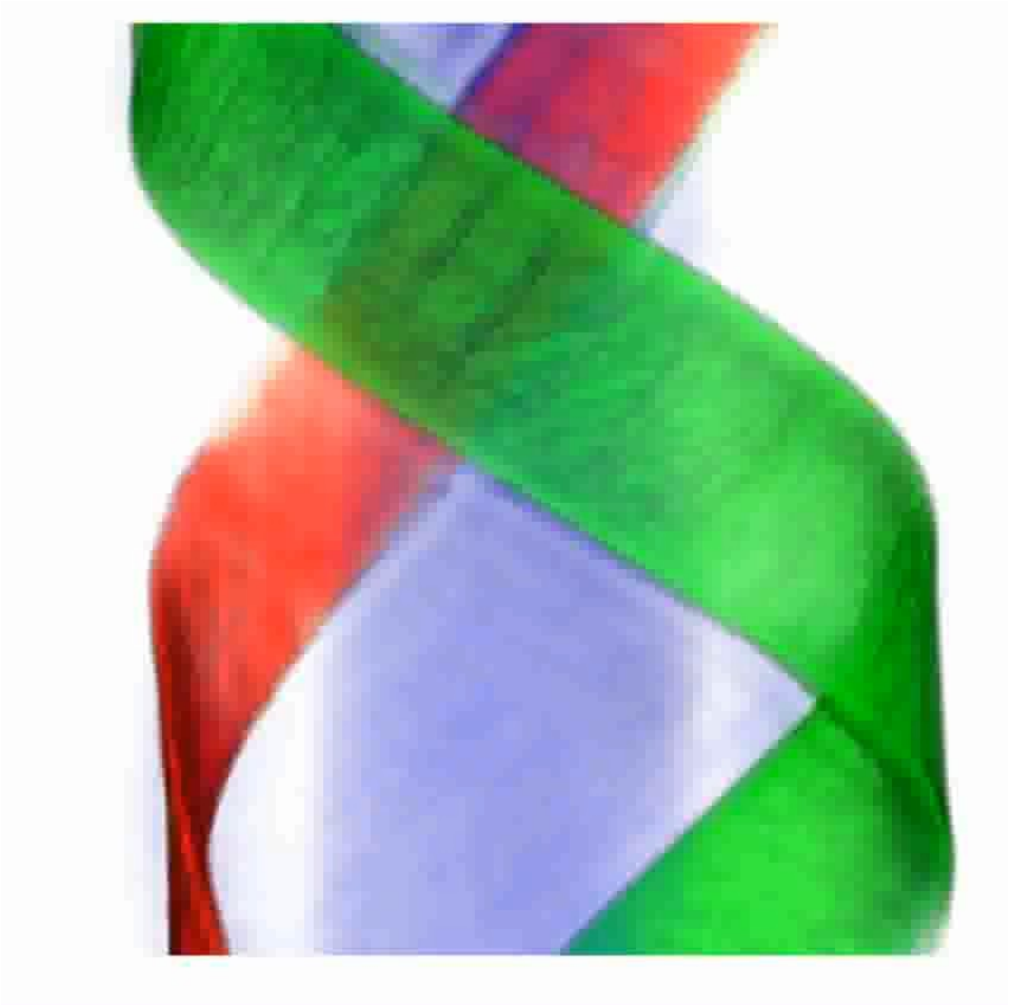
Conclusion

- Spectral CT is the future of X-ray imaging
  - possible thanks to energy sensitive pixel detectors
- Energy response function:
  - EITHER solve charge sharing (→ Medipix3)
  - OR full characterization
- Need to develop new reconstruction techniques



To download the thesis:

- The library of the University of Amsterdam: http://dare.uva.nl/record/1/432998
- The Nikhef library: http://www.nikhef.nl/pub/services/newbiblio/theses.php
- The CERN thesis database: http://cds.cern.ch/record/1971202/?ln=it



To contact me:

- enrico.junior.schioppa@cern.ch

Links:

- ctreco SVN repository: https://svnweb.cern.ch/cern/wsvn/ctreco
- My Twiki: https://twiki.cern.ch/twiki/bin/view/Main/EnricoJuniorSchioppa?forceShow=1

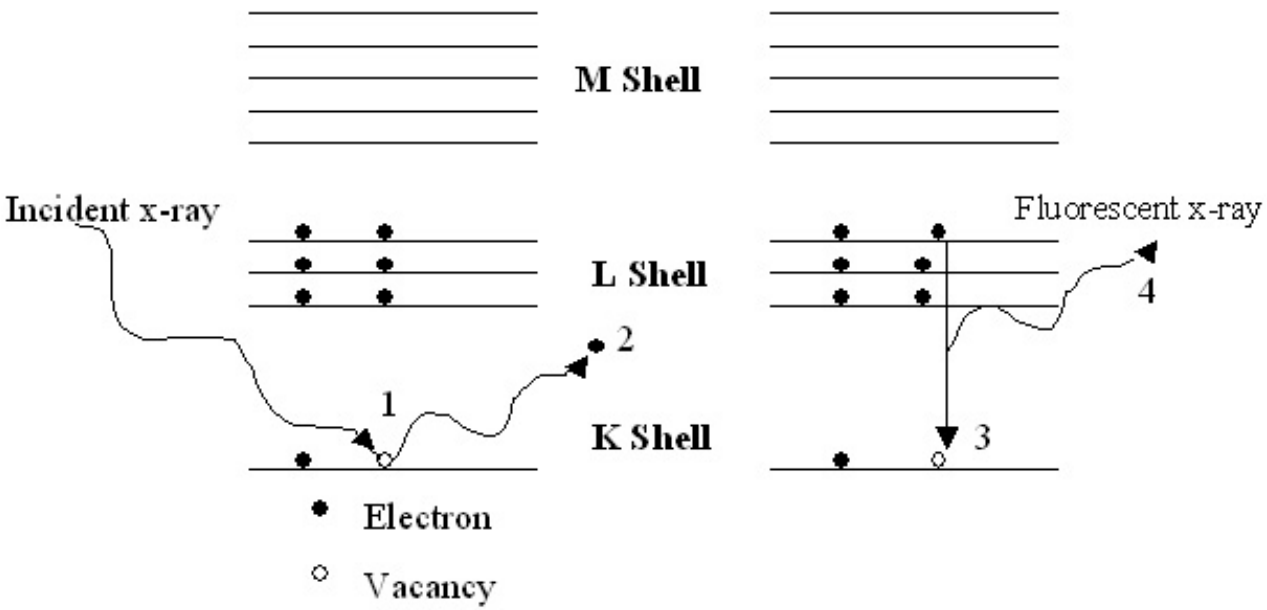
BACKUP

Threshold calibration with X-ray fluorescence

Photon energy ↔ discriminator voltage

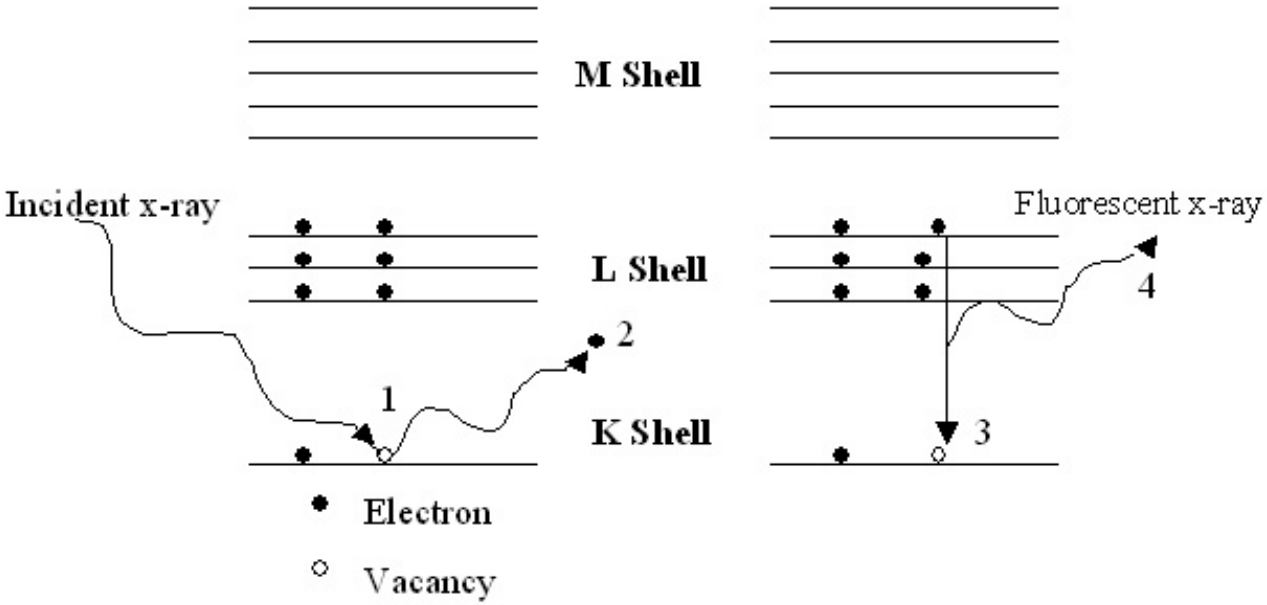
Threshold calibration with X-ray fluorescence

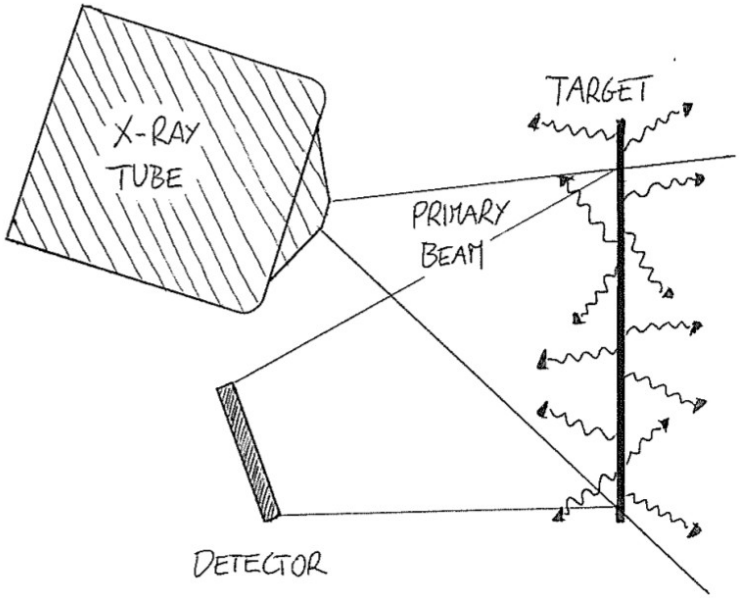
Photon energy ↔ discriminator voltage



Threshold calibration with X-ray fluorescence

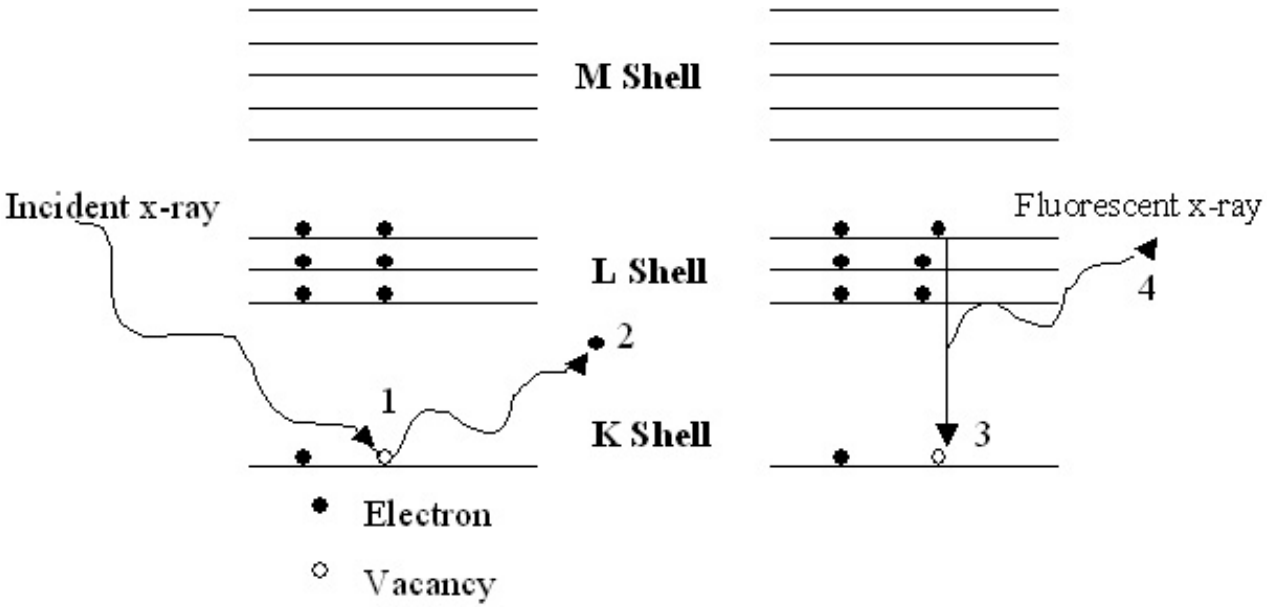
Photon energy ↔ discriminator voltage

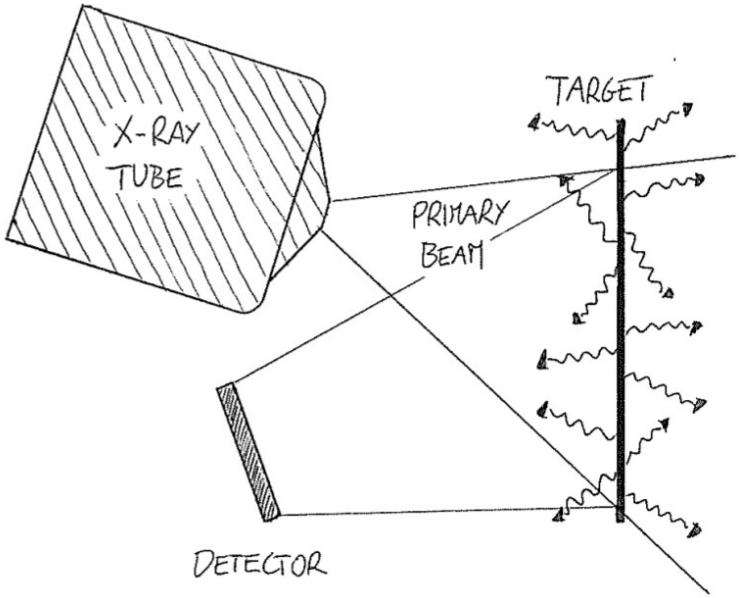


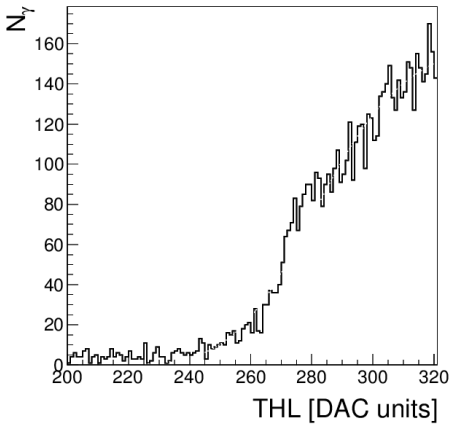


Threshold calibration with X-ray fluorescence

Photon energy ↔ discriminator voltage



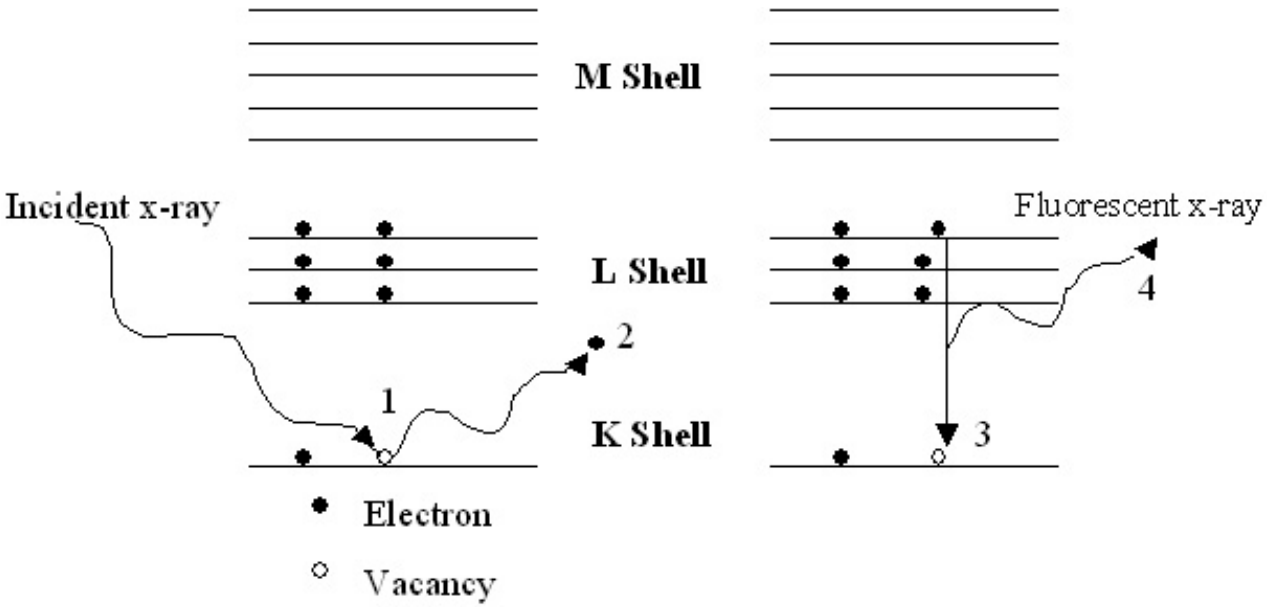


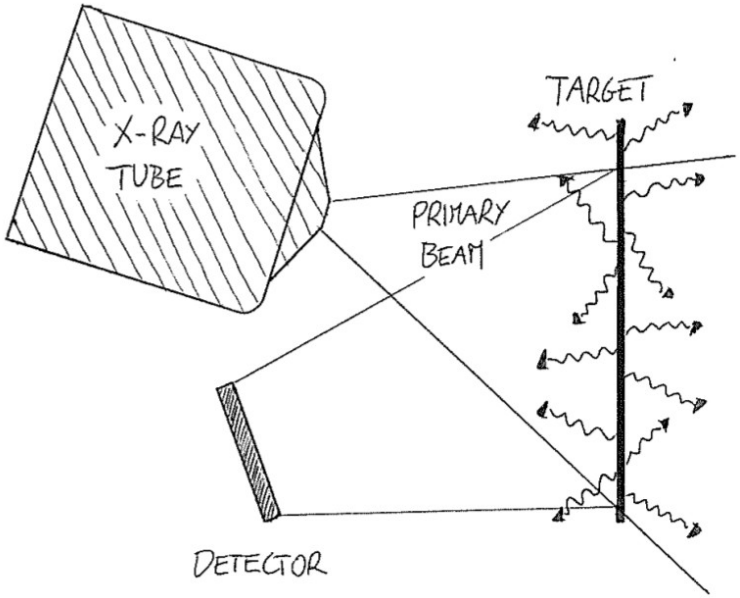


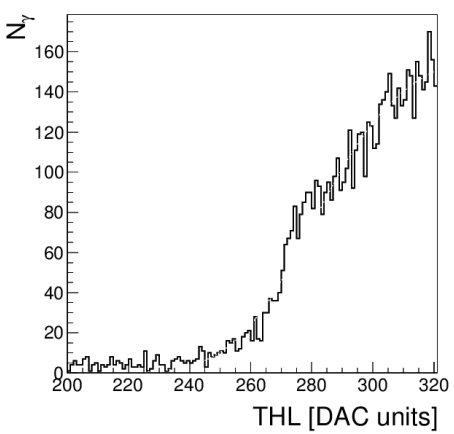
1 – acquire 65k spectra

Threshold calibration with X-ray fluorescence

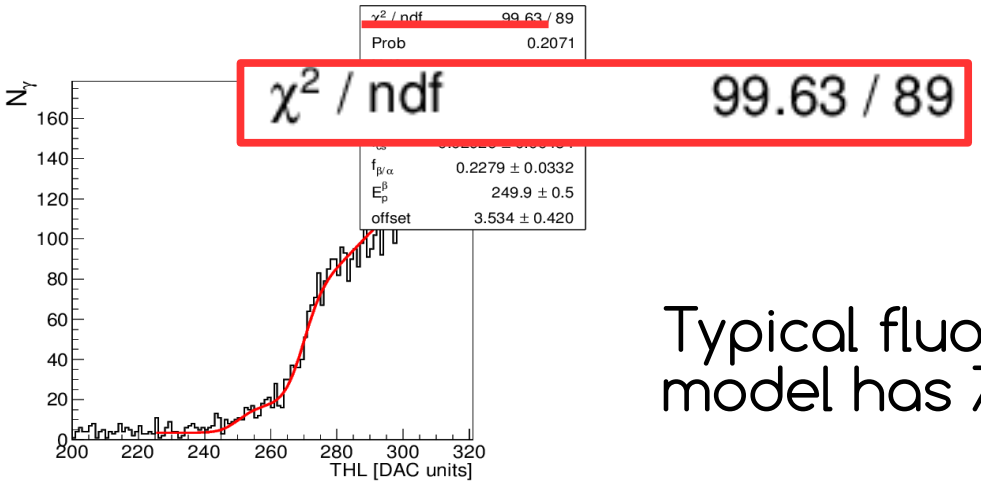
Photon energy ↔ discriminator voltage







1 – acquire 65k spectra



1 – do 65k fits

Typical fluorescence model has 7 parameters

RooFit for computed tomography: working plan

me

- Implement expectation value
- Implement probability density function (PDF)
- Simulate data
- reconstruct

W. Verkerke

- Optimize data handling
- Identify and disable "useless" routines
- Optimize PDF handling

RooFit

```
enricojr@enricojr-Vostro-3350 ~ $
enricojr@enricojr-Vostro-3350 ~ $ root -l
root [0] using namespace RooFit

RooFit v3.59 -- Developed by Wouter Verkerke and David Kirkby
                Copyright (C) 2000-2013 NIKHEF, University of California & Stanford University
                All rights reserved, please read http://roofit.sourceforge.net/license.txt

root [1] .q
enricojr@enricojr-Vostro-3350 ~ $
```

RooFit

```
enricojr@enricojr-Vostro-3350 ~ $
enricojr@enricojr-Vostro-3350 ~ $ root -l
root [0] using namespace RooFit

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                All rights reserved, please read http://roofit.sourceforge.net/license.txt

root [1] .q
enricojr@enricojr-Vostro-3350 ~ $
```
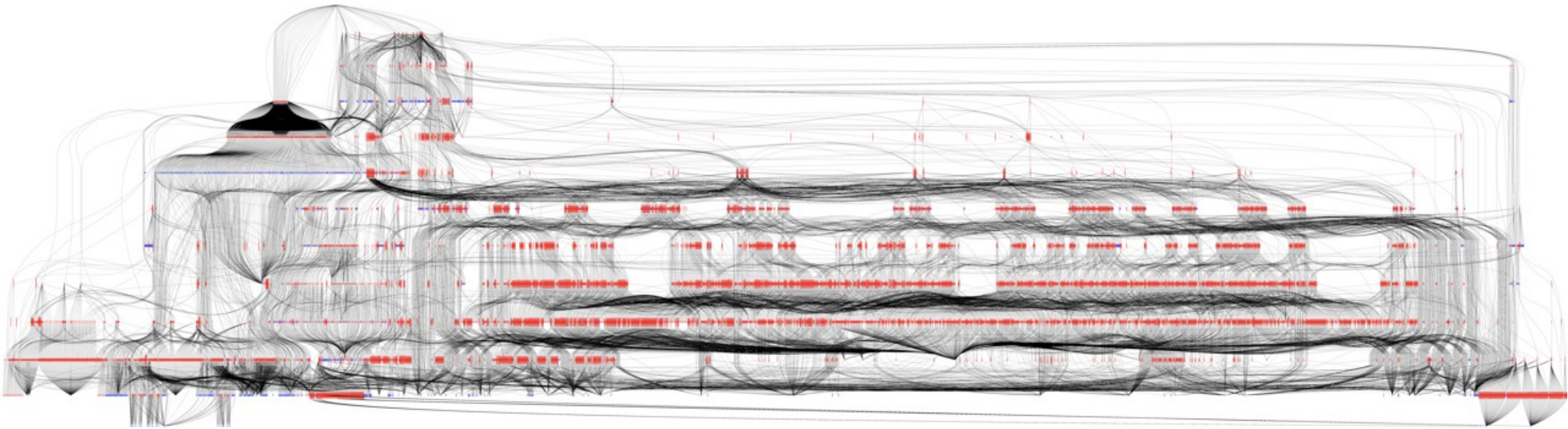
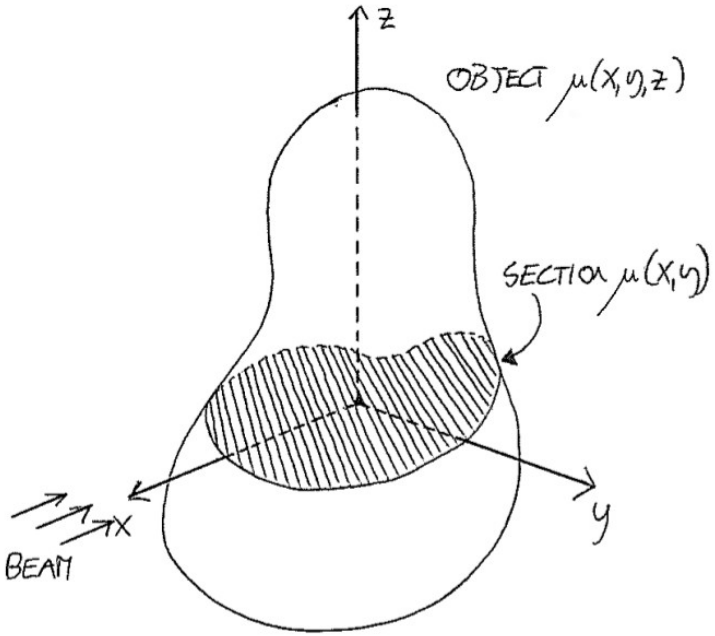



The full Higgs combination model, 23000 functions, 1600 parameters

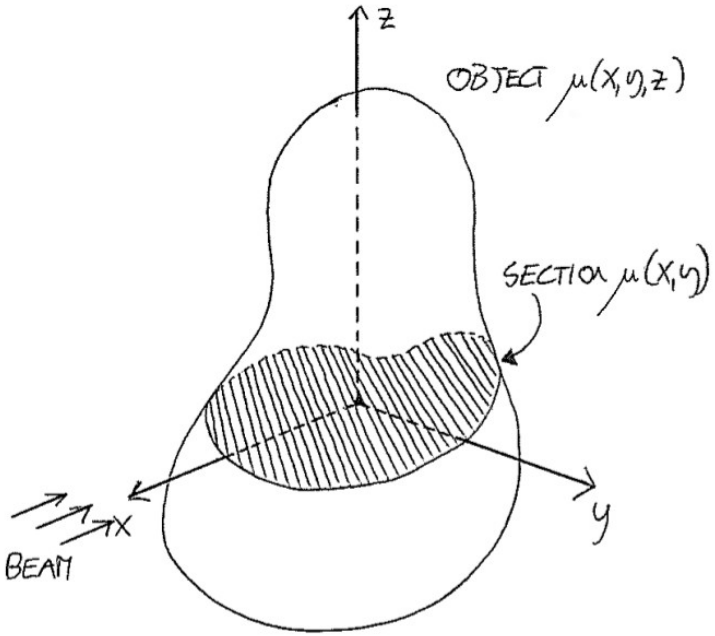
Image credit http://cds.nyu.edu/projects/collaborative-statistical-modeling/

Some counting...



Focus on one slice only

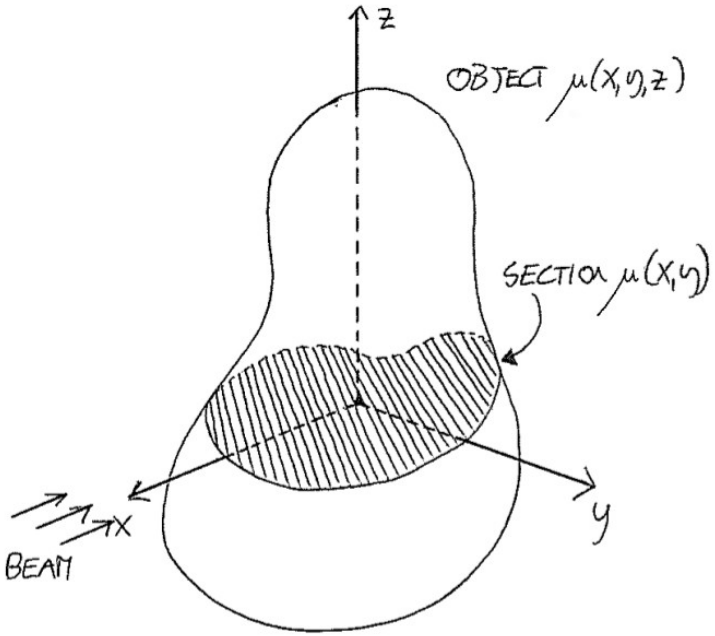
Some counting...



Focus on one slice only

$$N_{l,\theta,t}$$

Some counting...

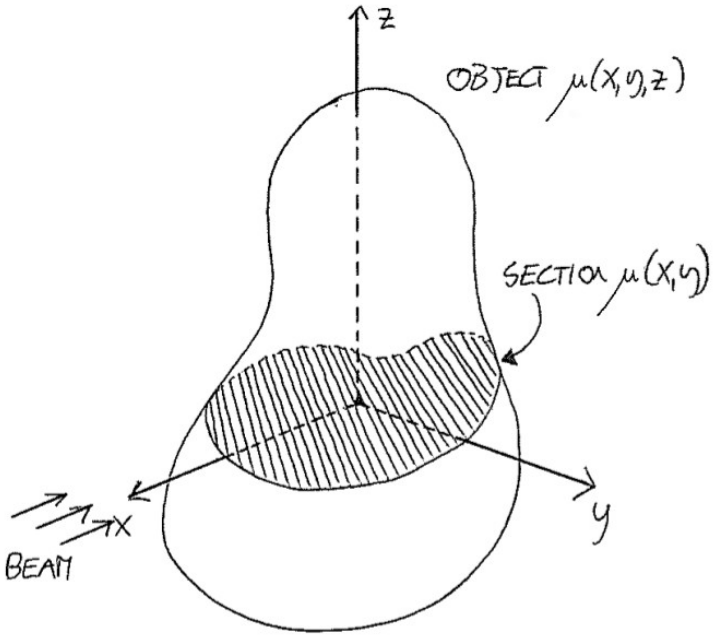


Focus on one slice only

$$N_{l,\theta,t}$$

100

Some counting...

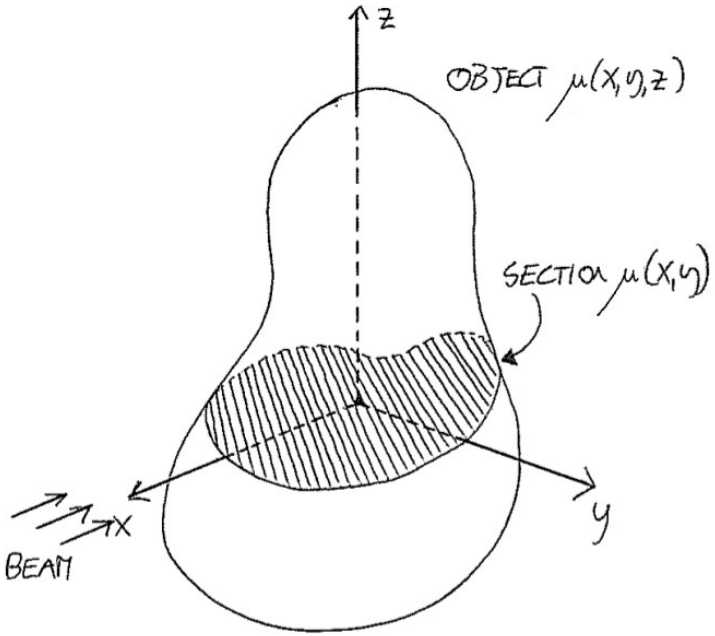


Focus on one slice only

$$N_{l,\theta,t}$$

100 180

Some counting...

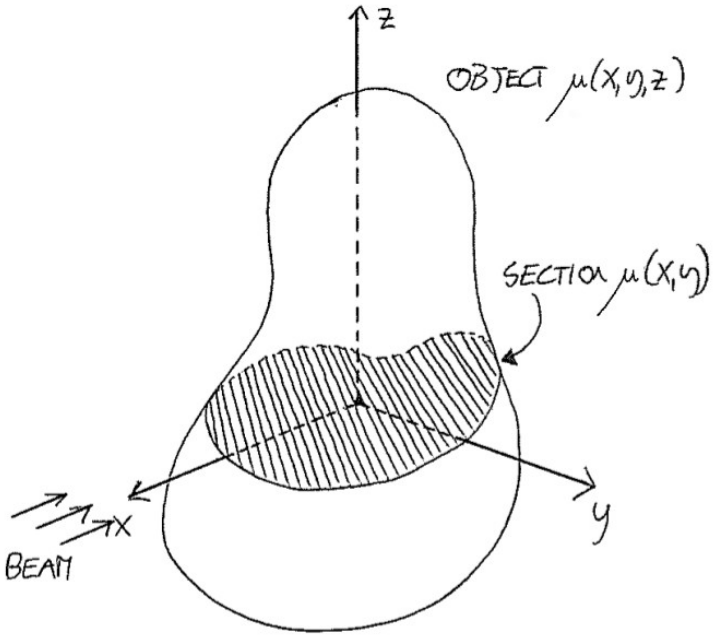


Focus on one slice only

$$N_{l,\theta,t}$$

100 180 3

Some counting...

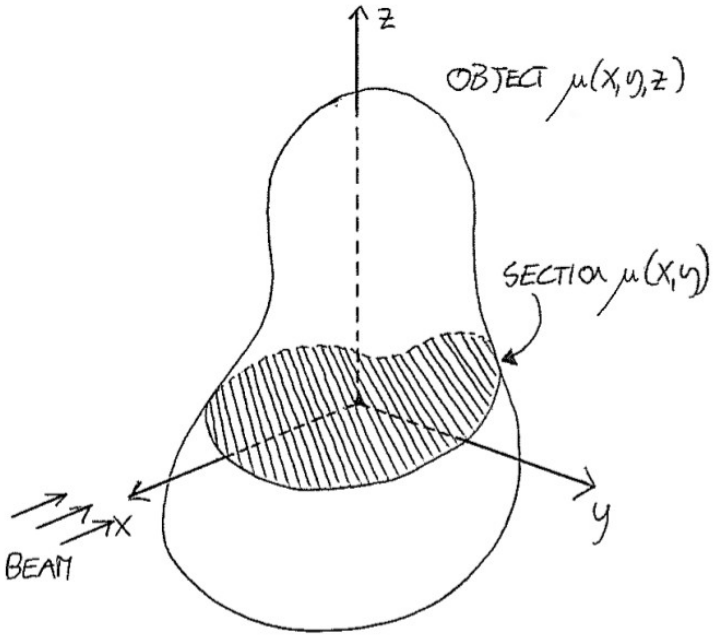


Focus on one slice only

$$N_{l,\theta,t} = 54\text{k}$$

100 180 3

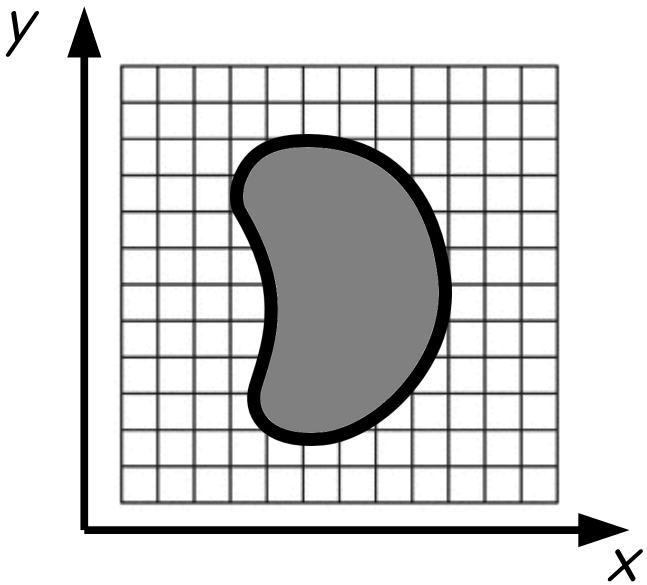
Some counting...



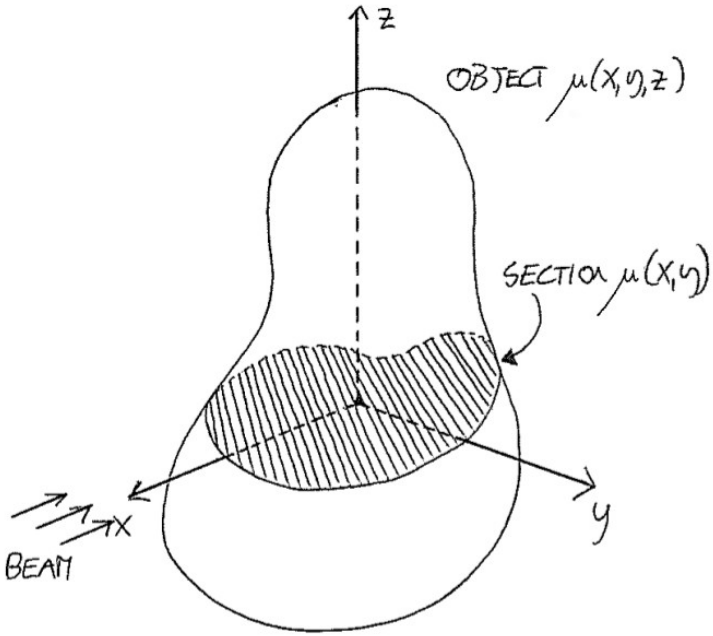
Focus on one slice only

$$N_{l,\theta,t} = 54\text{k}$$

100 180 3



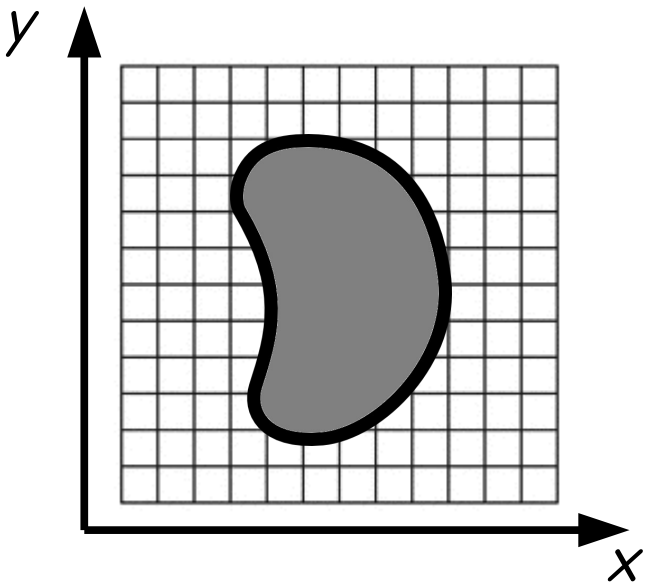
Some counting...



Focus on one slice only

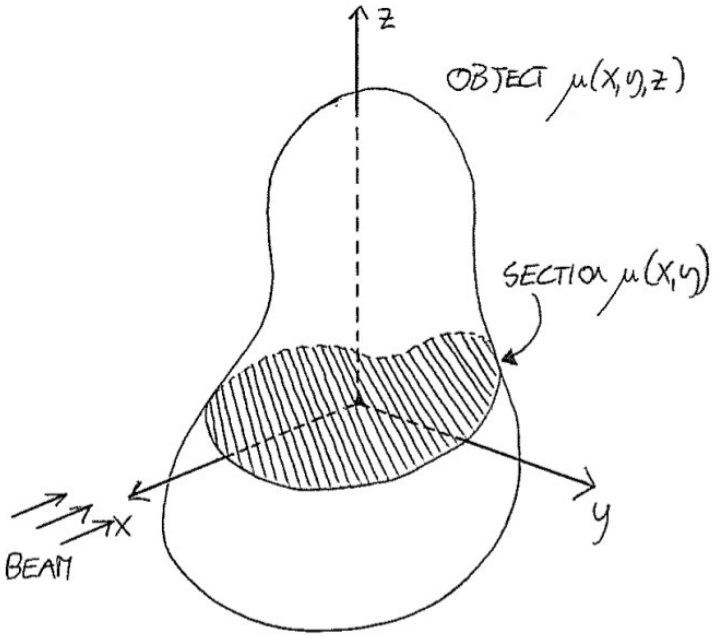
$$N_{l,\theta,t} = 54\text{k}$$

100 180 3



$$N_{voxels} = 100 \times 100 = 10\text{k}$$

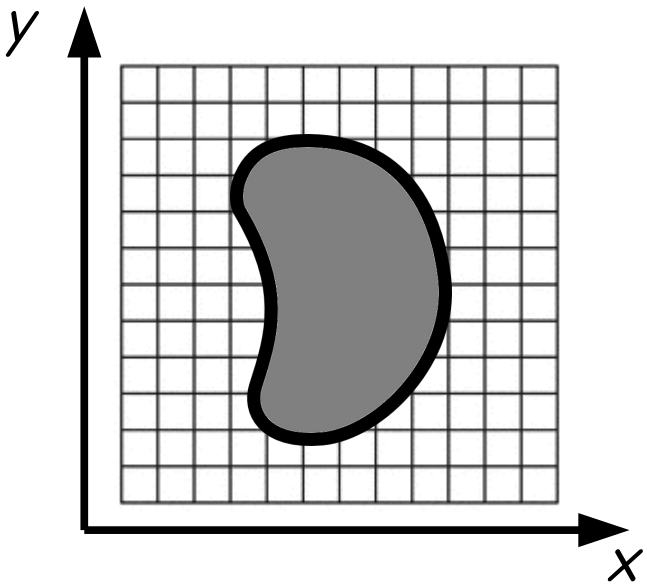
Some counting...



Focus on one slice only

$$N_{l,\theta,t} = 54\text{k}$$

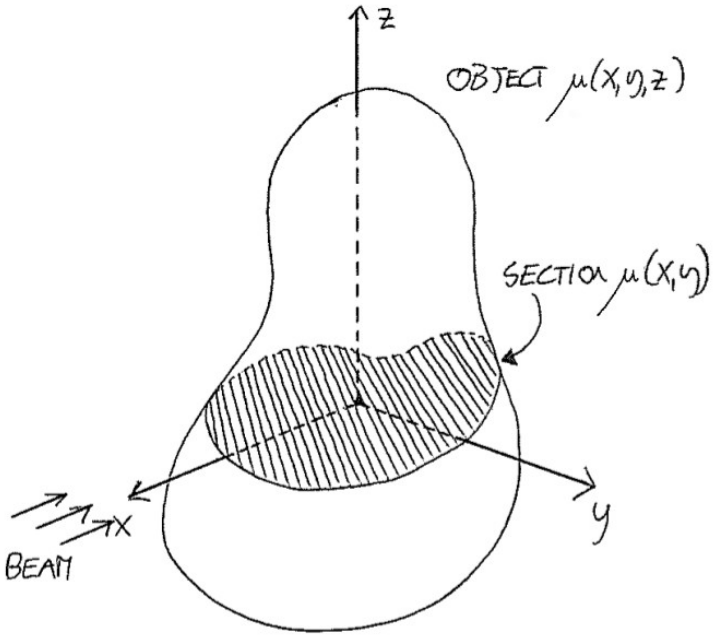
100 180 3



$$N_{voxels} = 100 \times 100 = 10\text{k}$$

$$N_{materials} = 3$$

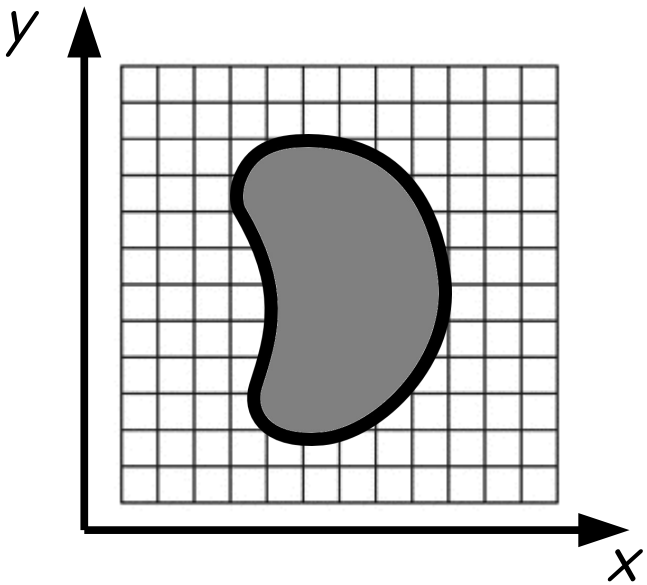
Some counting...



Focus on one slice only

$$N_{l,\theta,t} = 54\text{k}$$

100 180 3



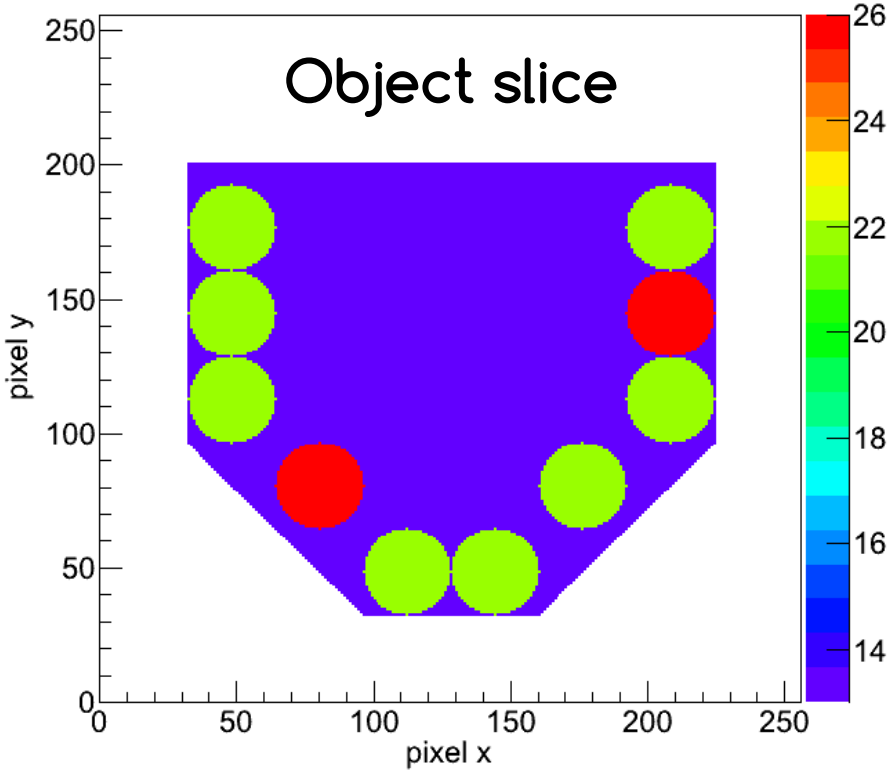
$$N_{voxels} = 100 \times 100 = 10\text{k}$$

$$N_{materials} = 3$$

$$dim(Img) = 30\text{k}$$

High energy physics → complex models, “few” parameters

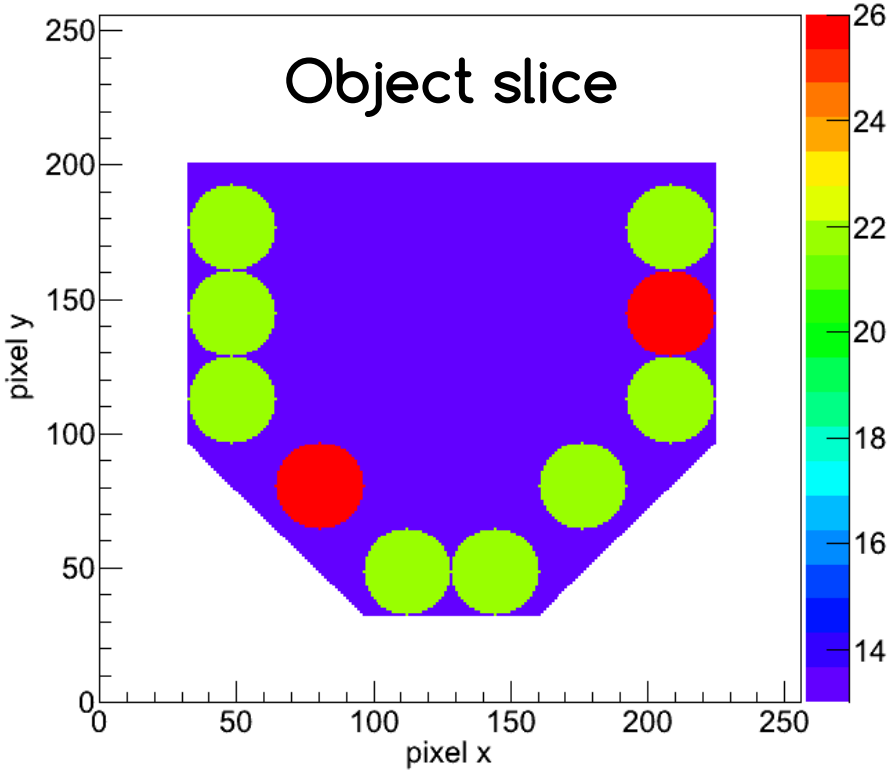
Computed Tomography → “simple” models, many parameters



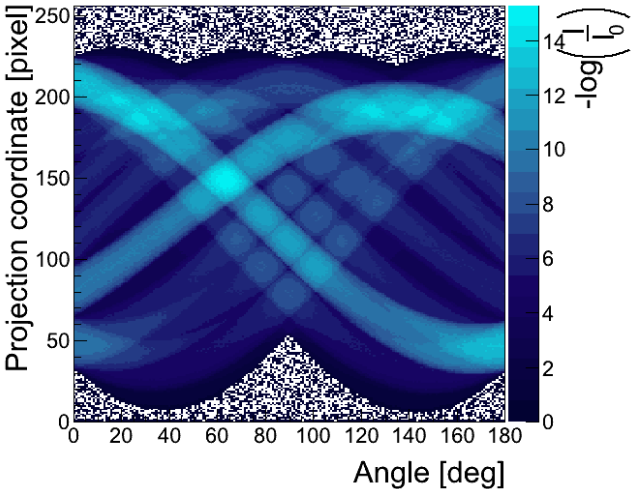
Blue = Al
Green = Ti
Red = Fe

$\mu_m(s, E)$ (truth)

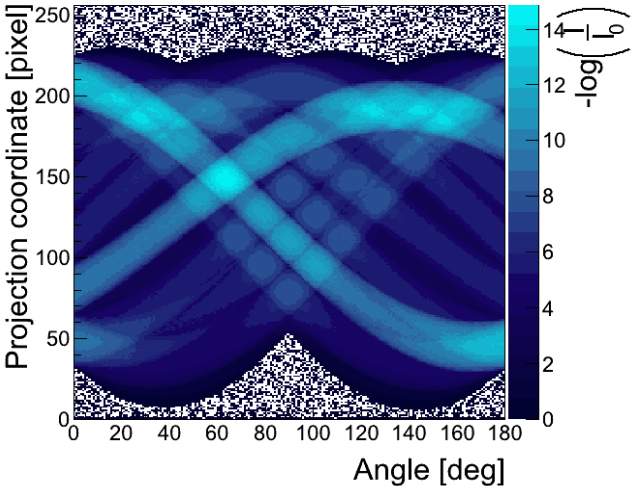
Use big formula



Threshold
3 keV



Threshold
10 keV

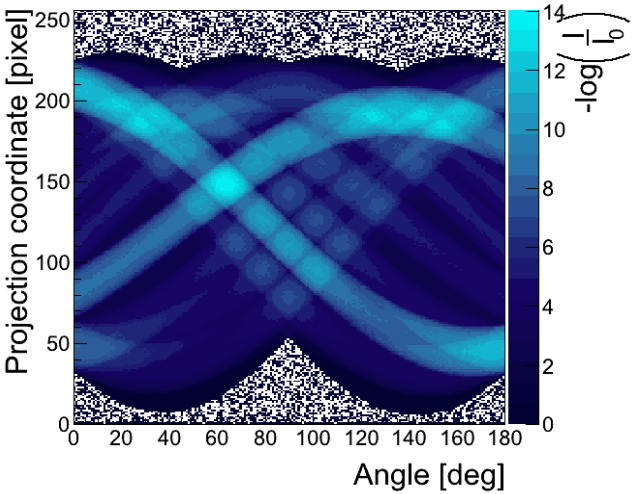


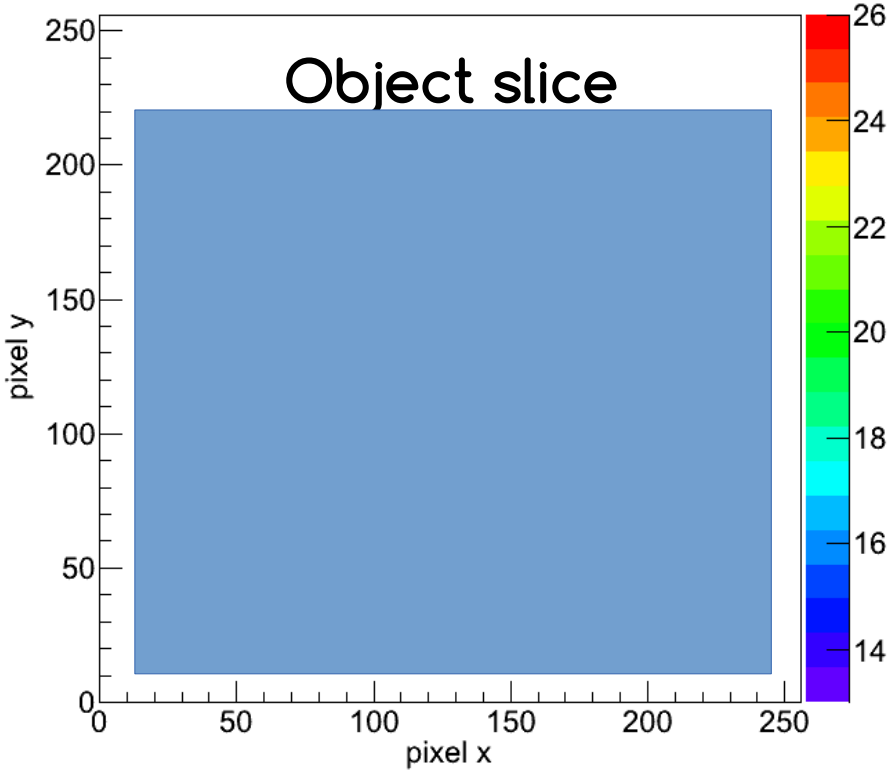
Blue = Al
Green = Ti
Red = Fe

$$\mu_m(s, E)$$ (truth)

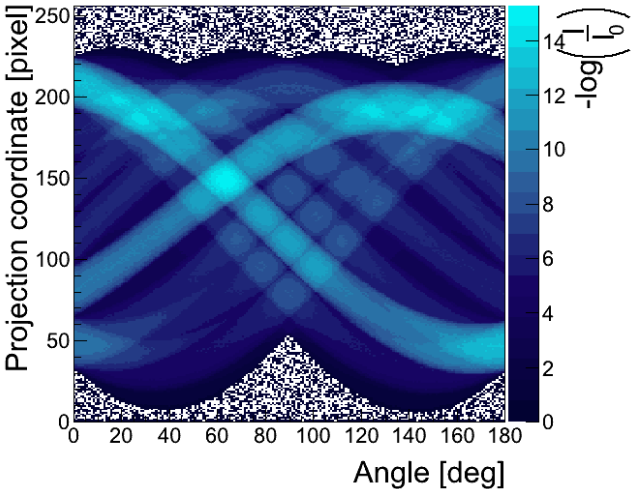
Use big formula

Threshold
20 keV

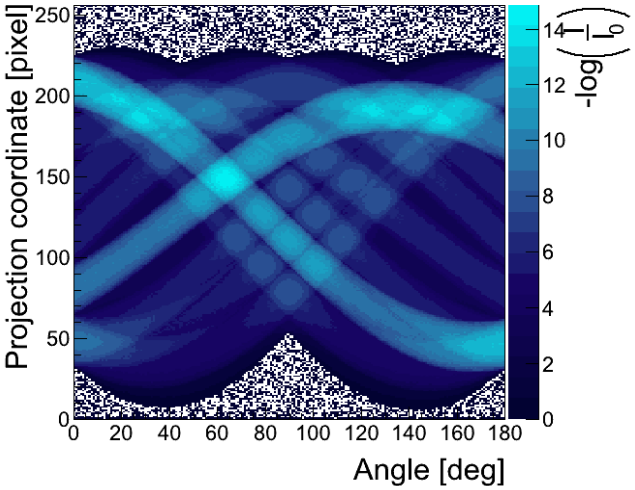




Threshold
3 keV



Threshold
10 keV

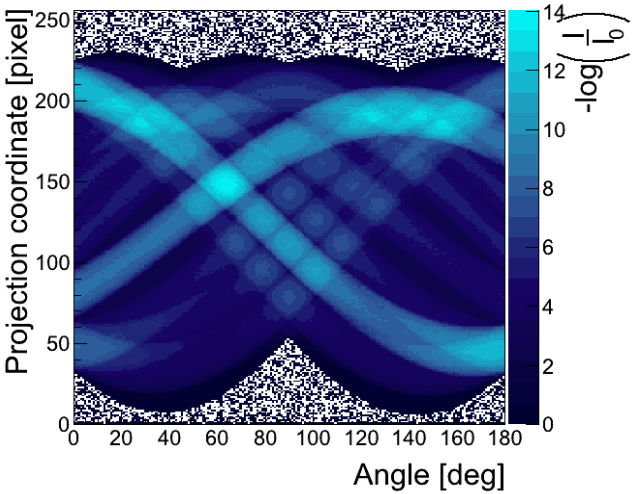


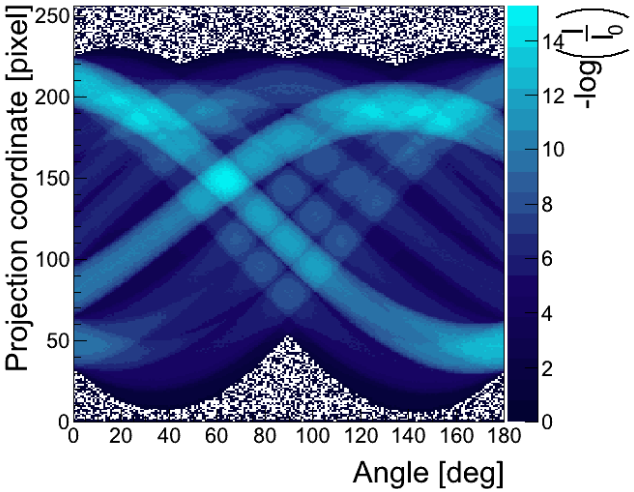
Blue = Al
Green = Ti
Red = Fe

$\mu_m(s, E)$ (truth)

Use big formula

Threshold
20 keV

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Angle [deg]
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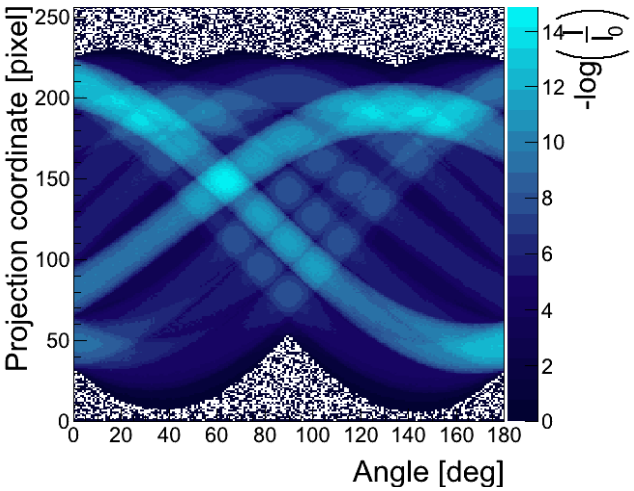
Projection coordinate [pixel]
Angle [deg]
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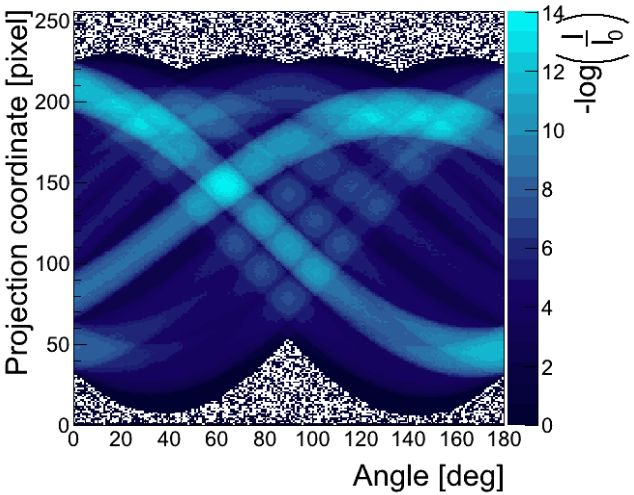
Projection coordinate [pixel]
Angle [deg]
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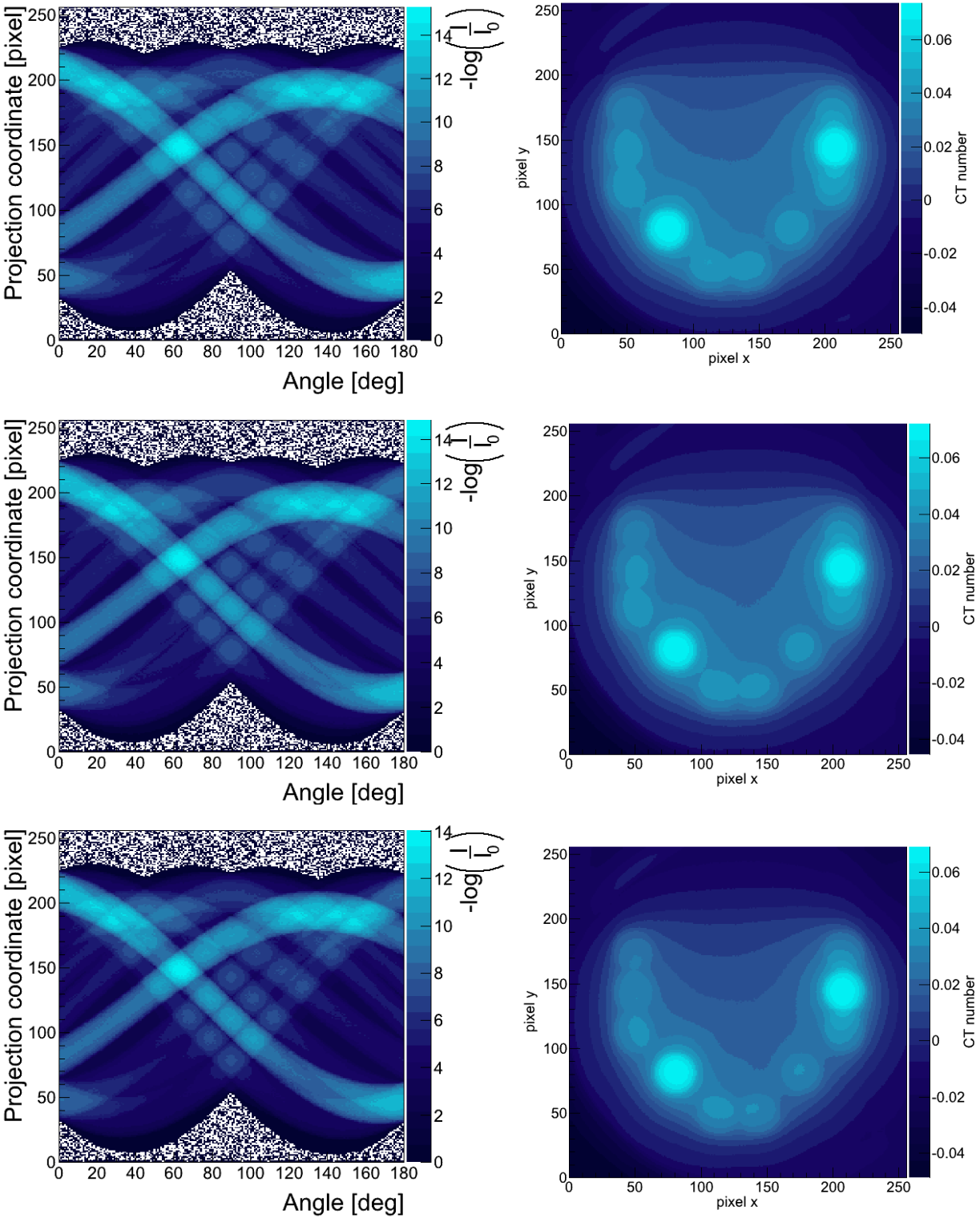
Projection coordinate [pixel]
Angle [deg]
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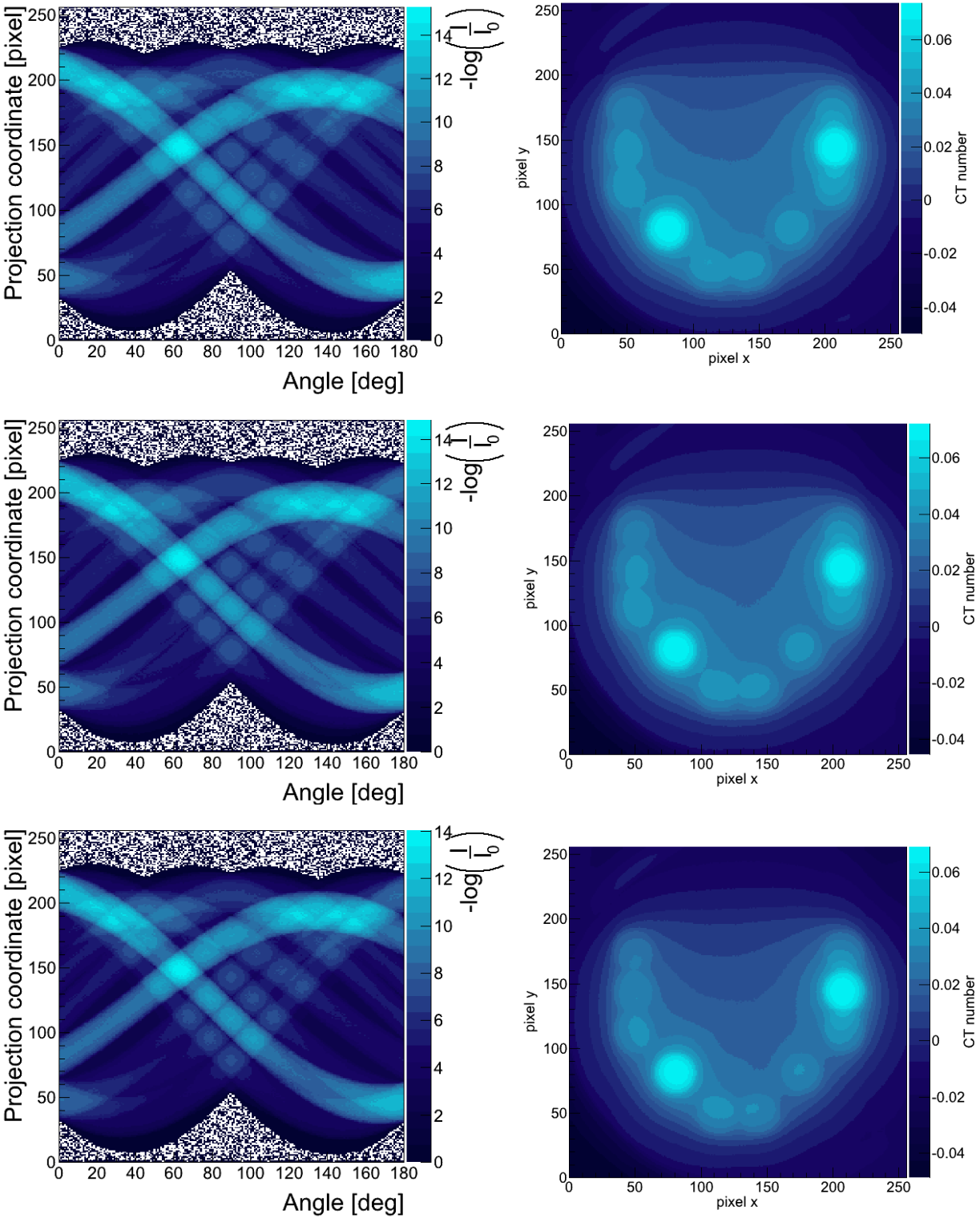
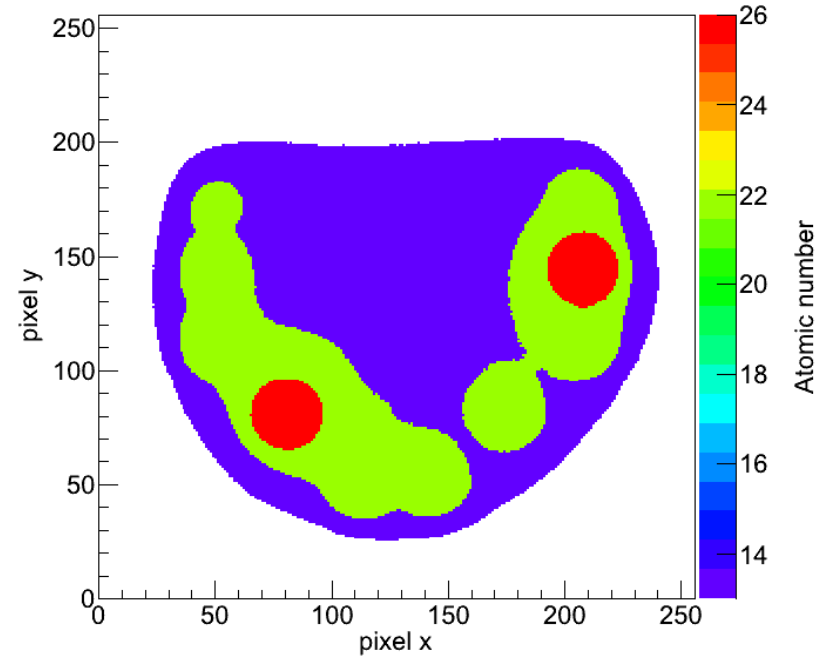
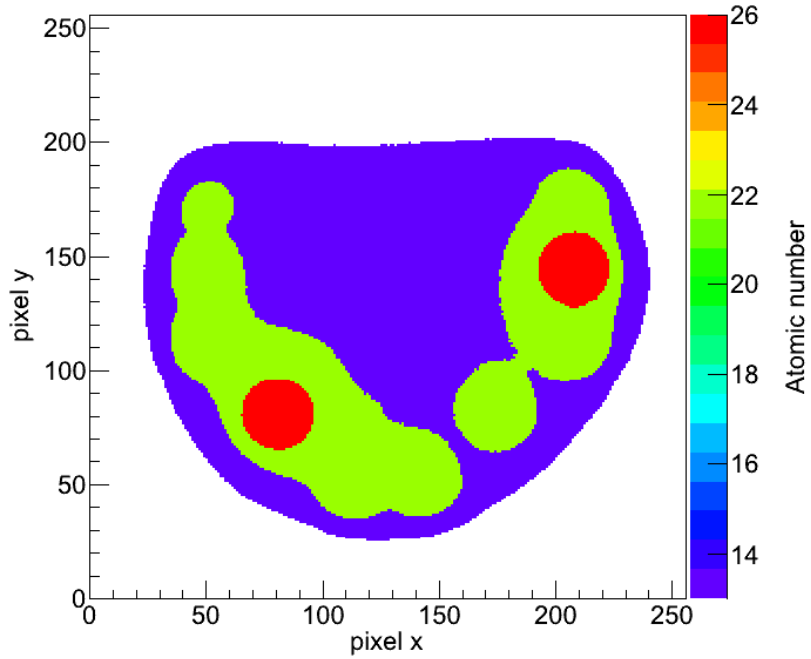
pixel y
pixel x
CT number





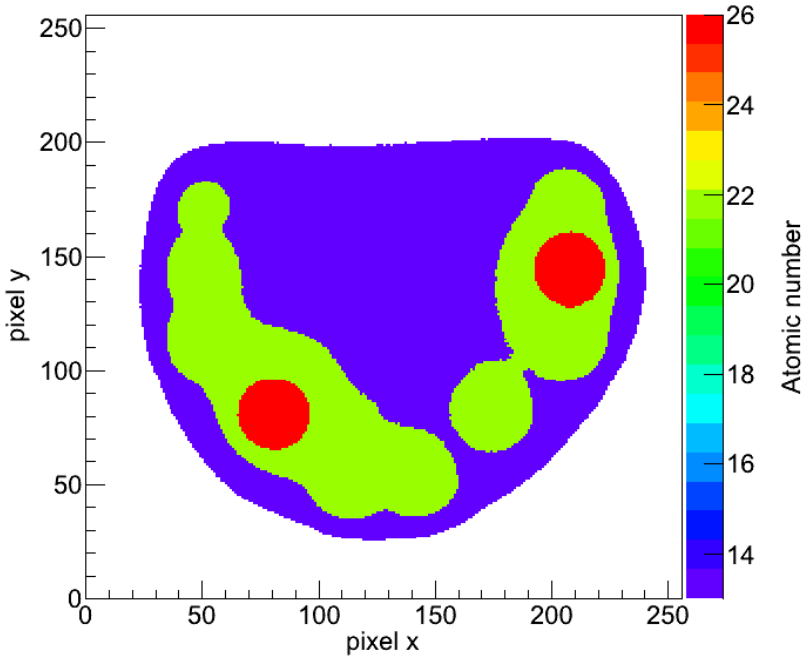
Blue = Al
Green = Ti
Red = Fe

$$\mu_m^0(s, E)$$



Blue = Al
Green = Ti
Red = Fe

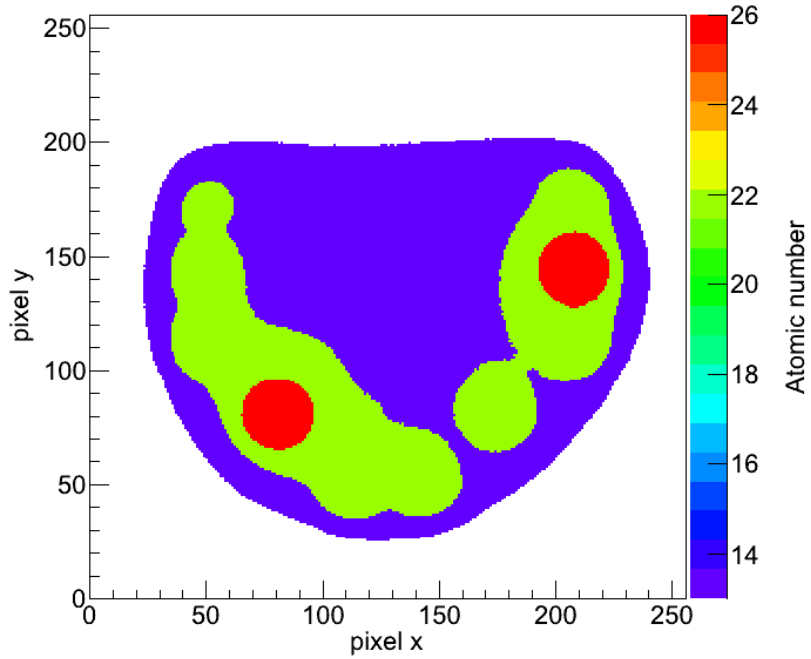
$$\mu_m^0(s, E)$$



Blue = Al
Green = Ti
Red = Fe

$$\mu_m^0(s, E)$$

Use big formula again

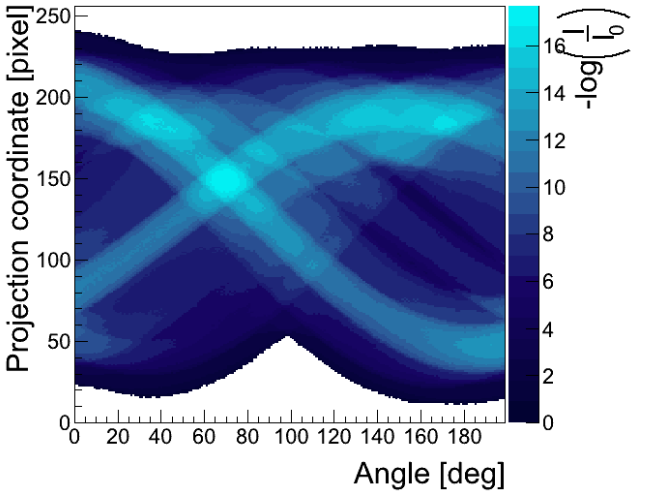


Blue = Al
Green = Ti
Red = Fe

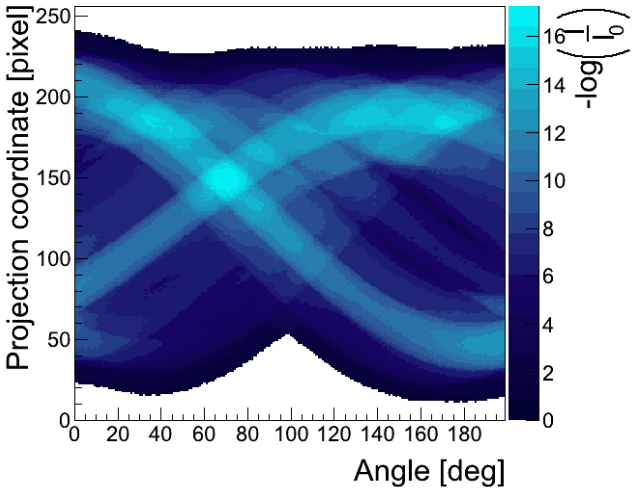
$$\mu_m^0(s, E)$$

Use big formula again

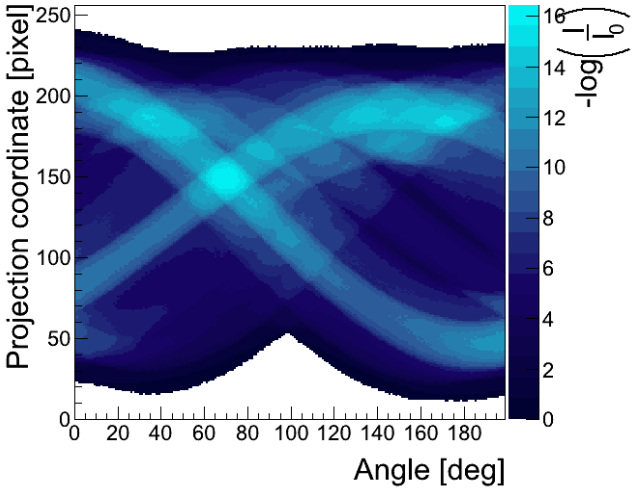
Threshold 3 keV

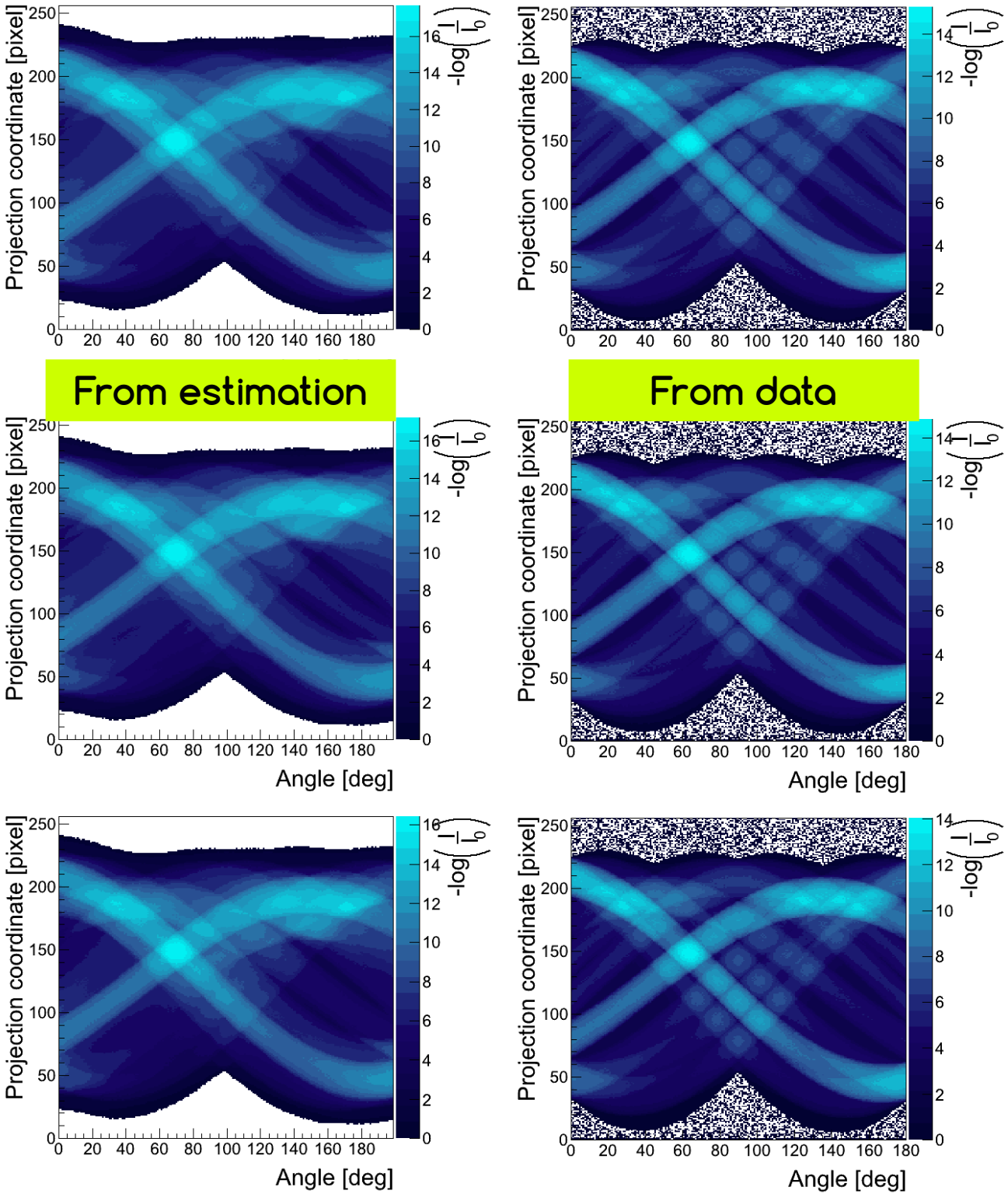


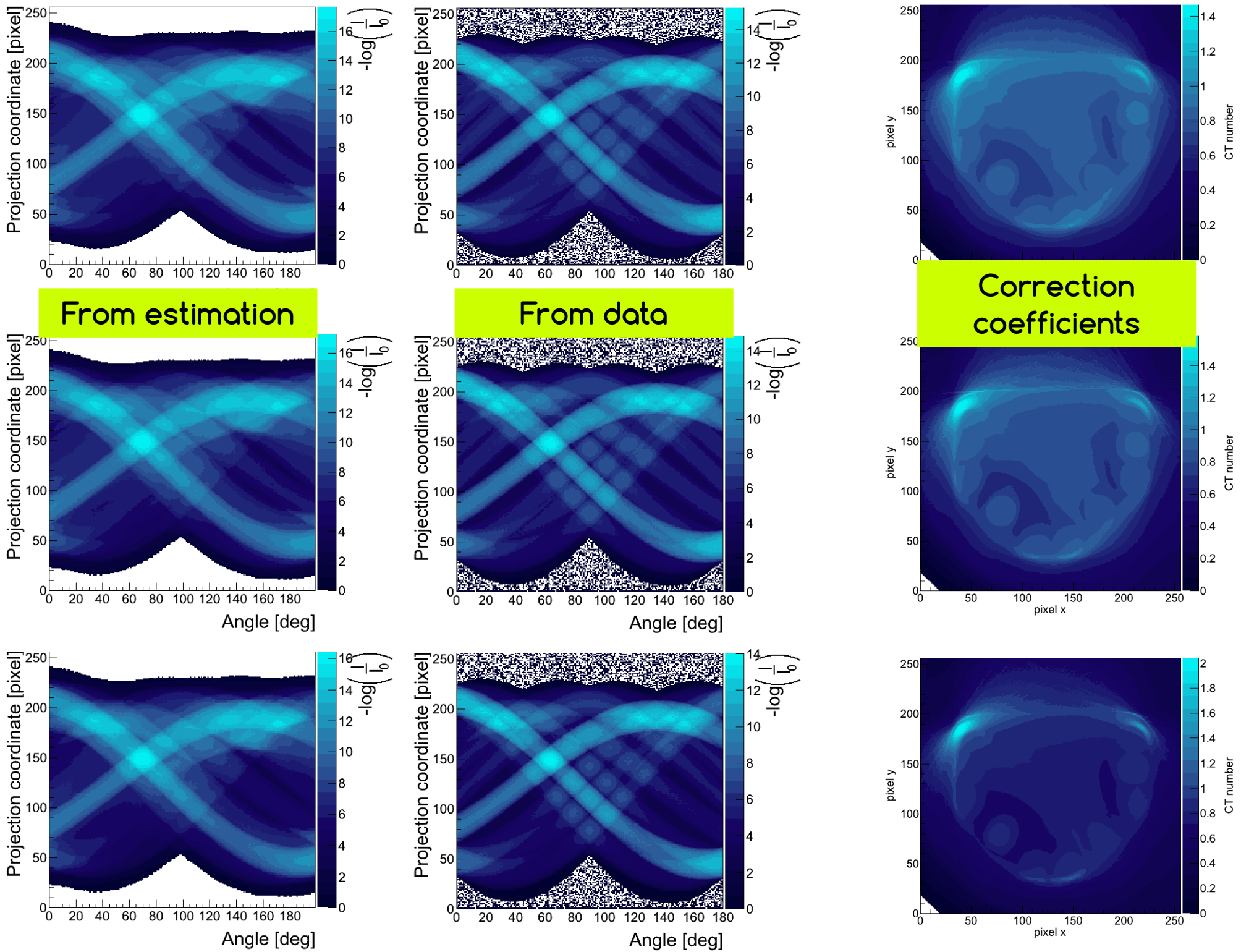
Threshold 10 keV

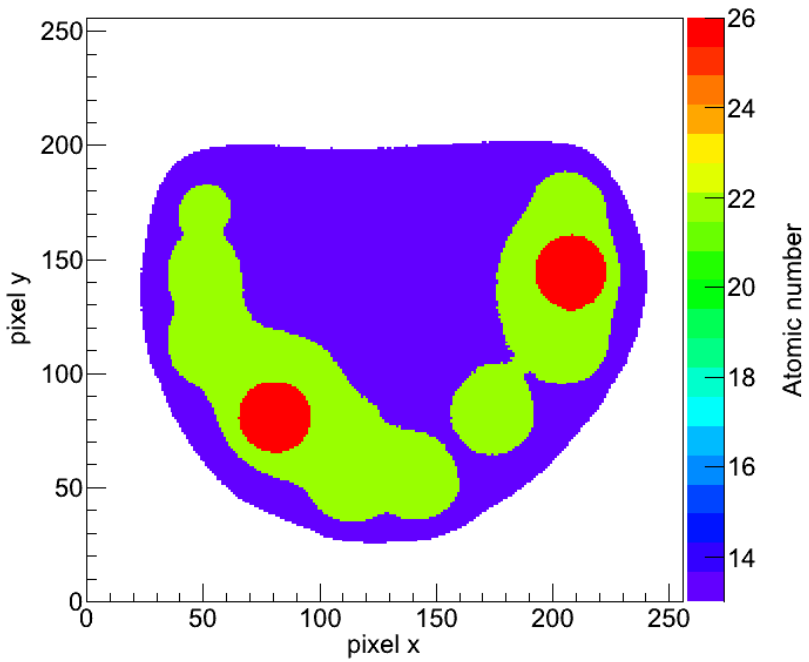


Threshold 20 keV



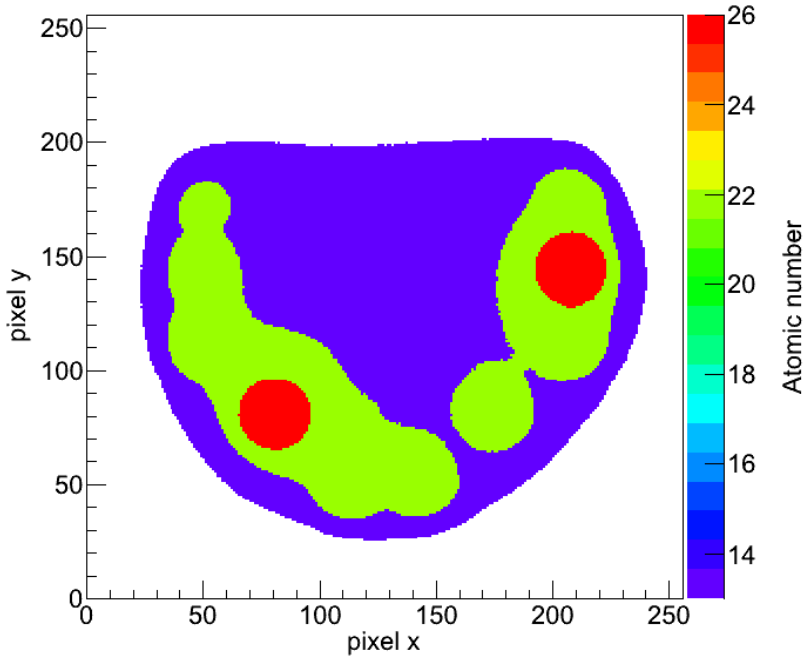

From estimation
From data
Projection coordinate [pixel]
Angle [deg]
$-\log\left(\frac{I}{I_0}\right)$

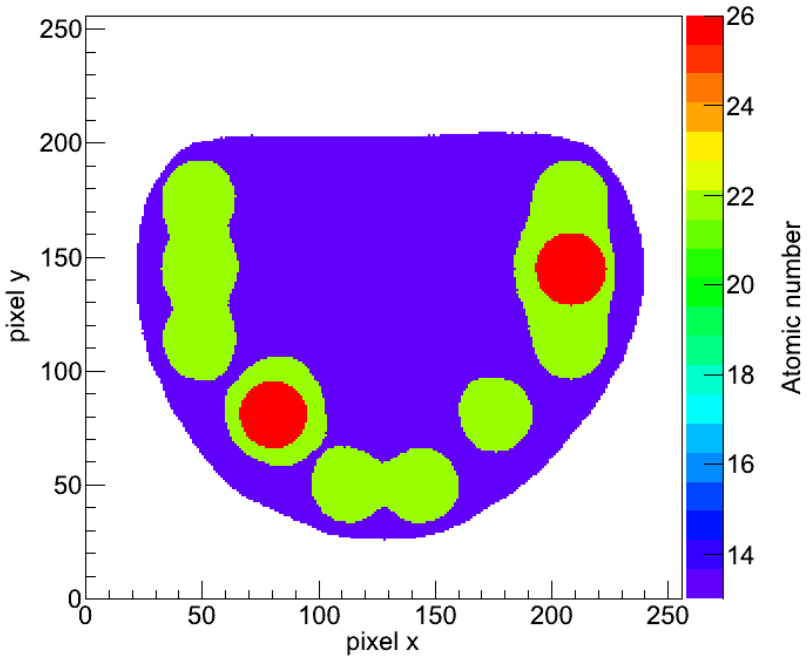

From estimation
From data
Correction coefficients
Projection coordinate [pixel]
Angle [deg]
-log(I/I0)
pixel x
pixel y
CT number



Blue = Al
Green = Ti
Red = Fe

$$\mu_m^0(s, E)$$





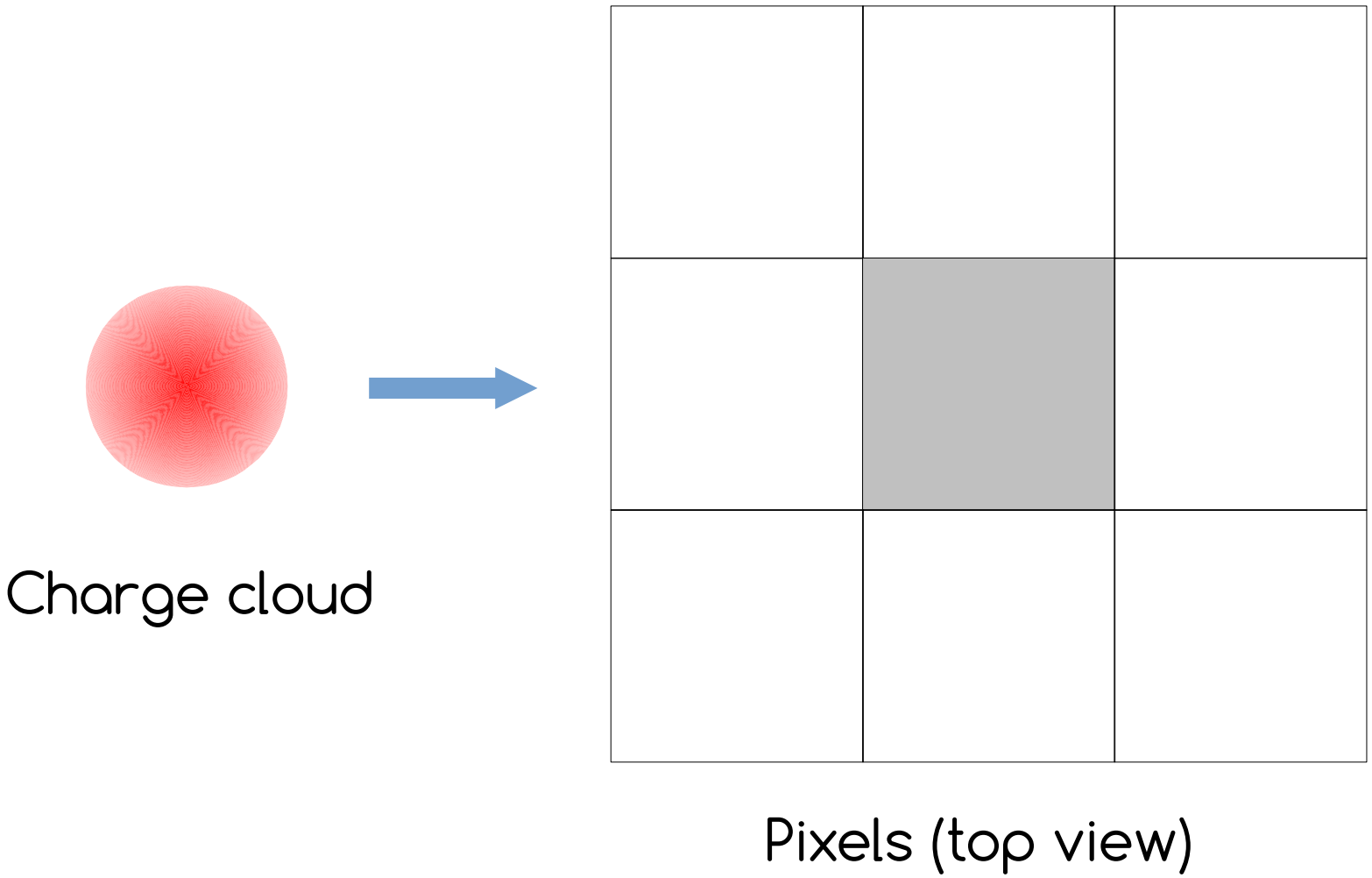
Blue = Al
Green = Ti
Red = Fe

$$\mu_m^0(s,E)$$

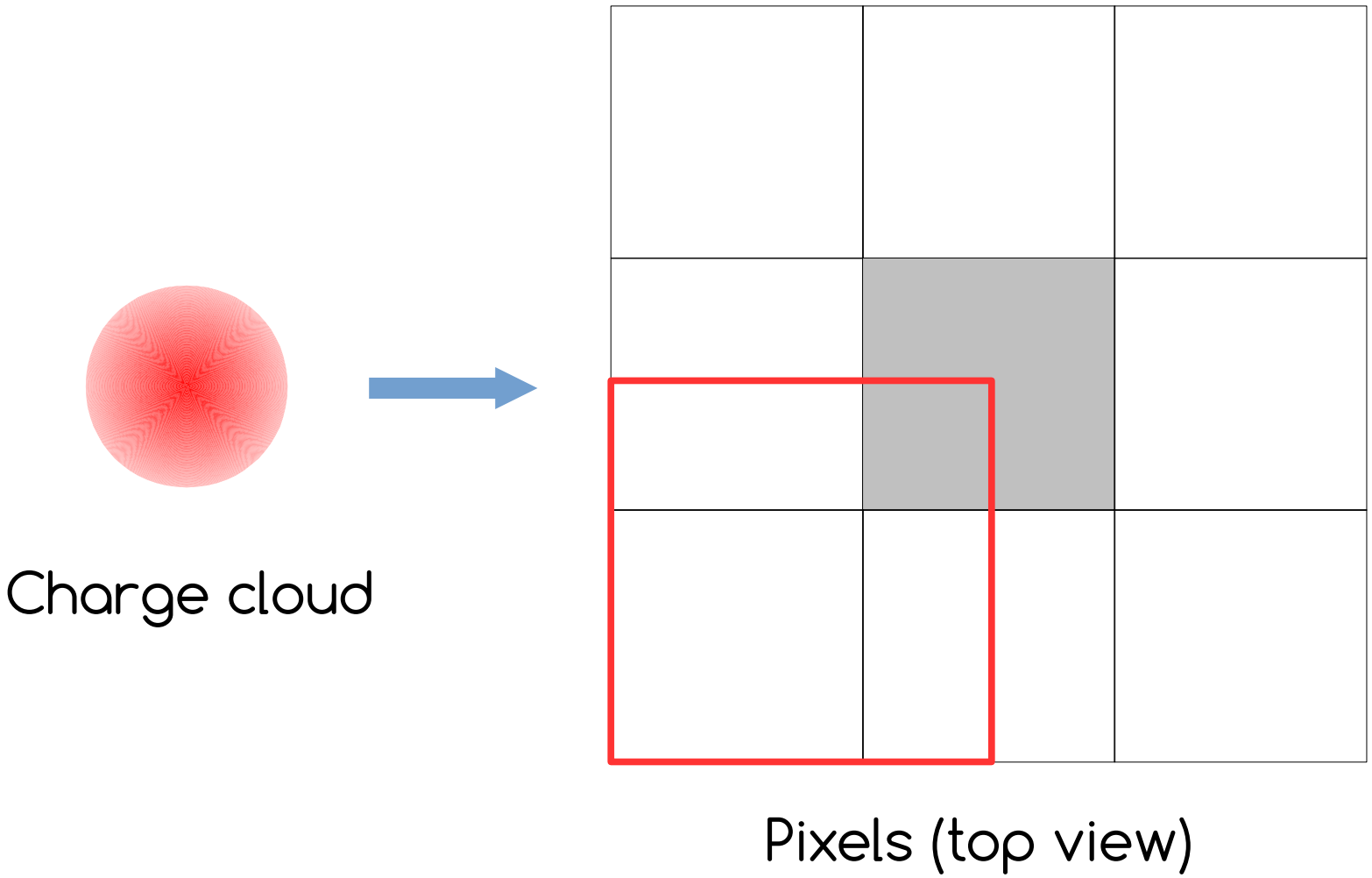
Blue = Al
Green = Ti
Red = Fe

$$\mu_m^1(s,E)$$

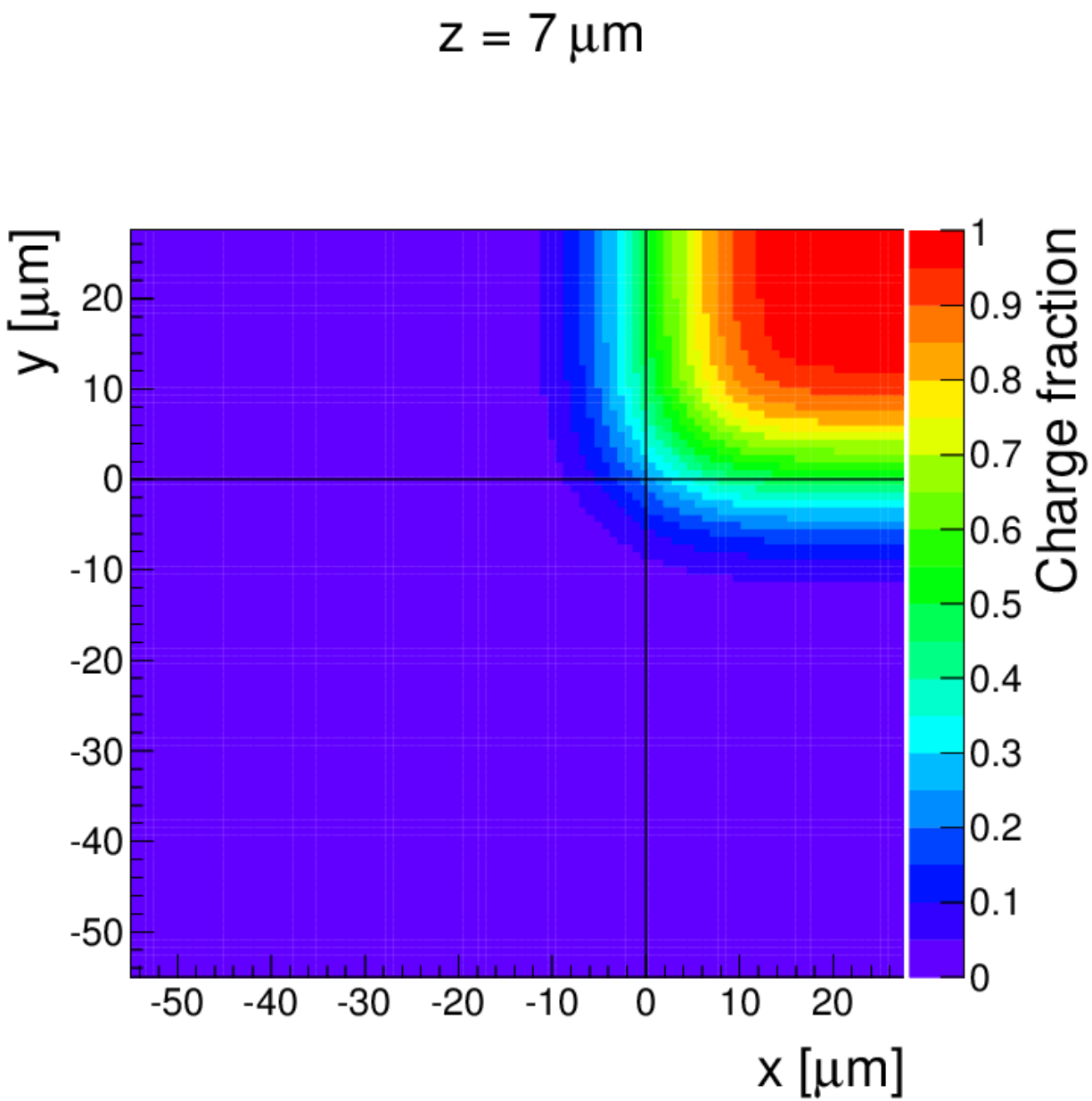
Calculating charge fraction in a pixel



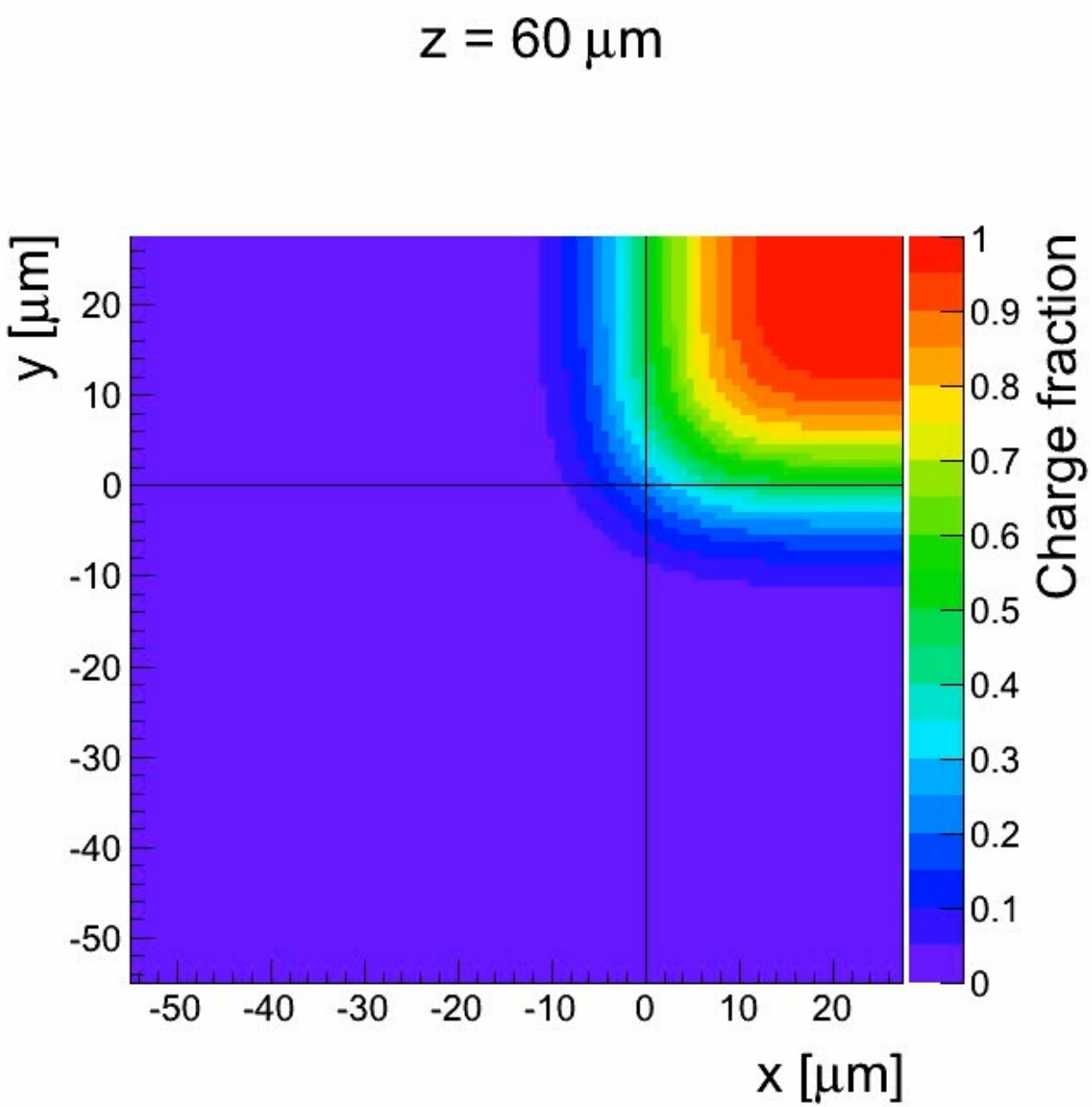
Calculating charge fraction in a pixel

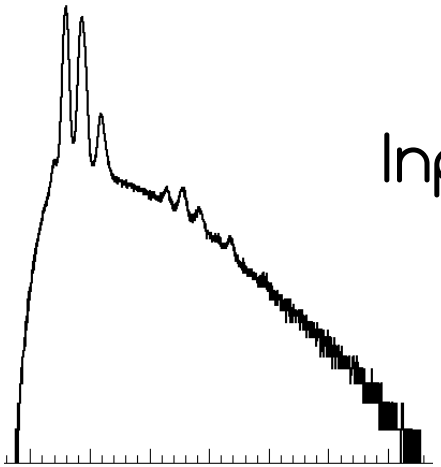


Calculating charge fraction in a pixel

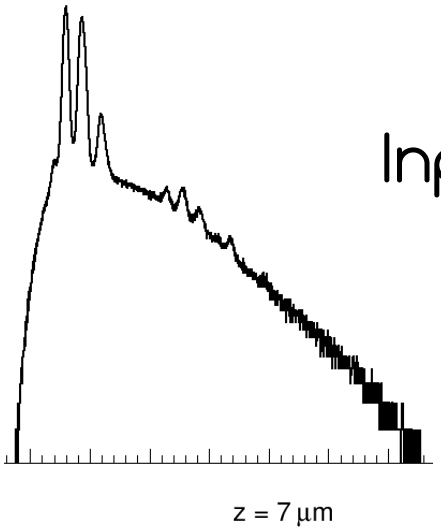


Calculating charge fraction in a pixel

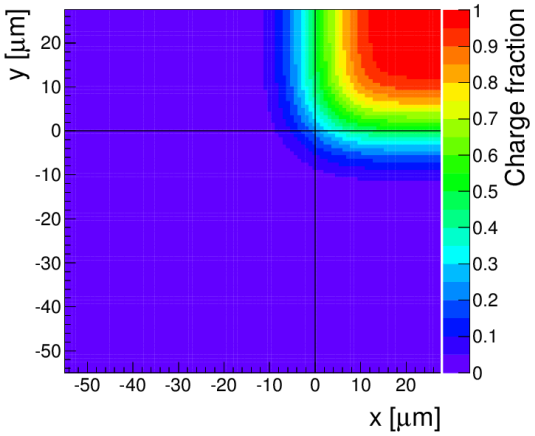




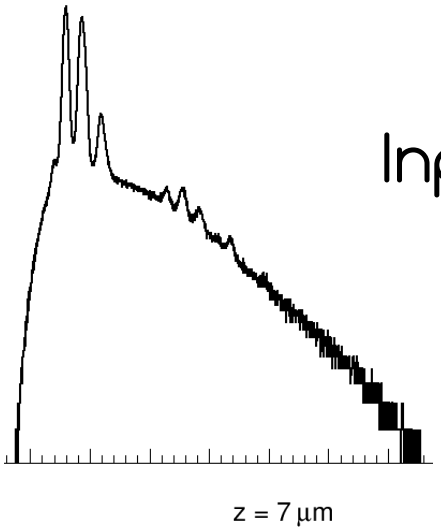
Input spectrum



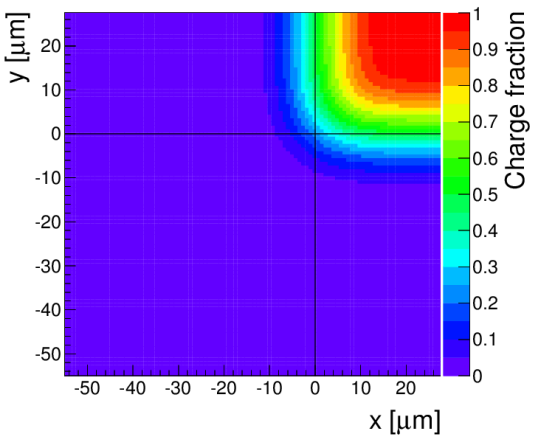
Input spectrum



Charge sharing

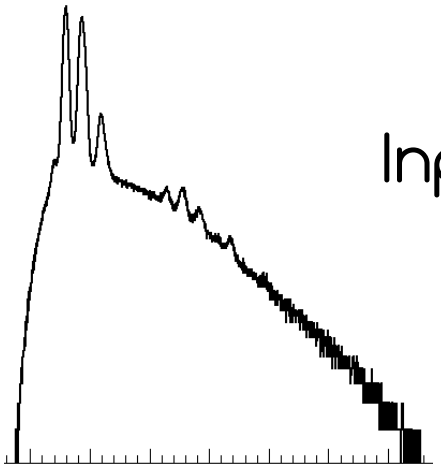


Input spectrum

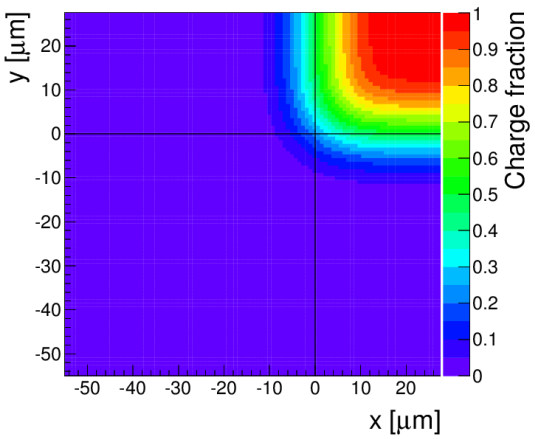


Charge sharing

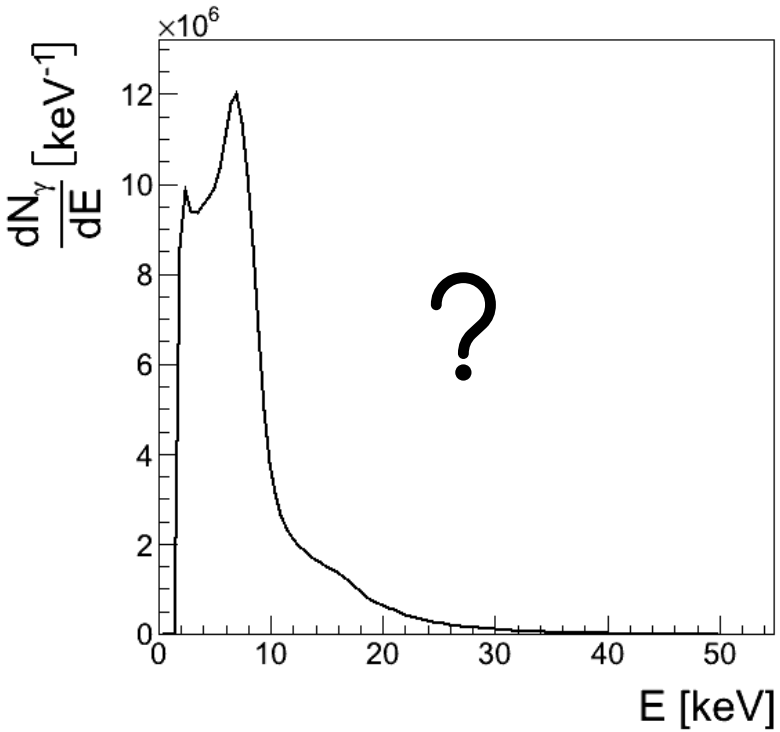
Si absorption curve



Input spectrum

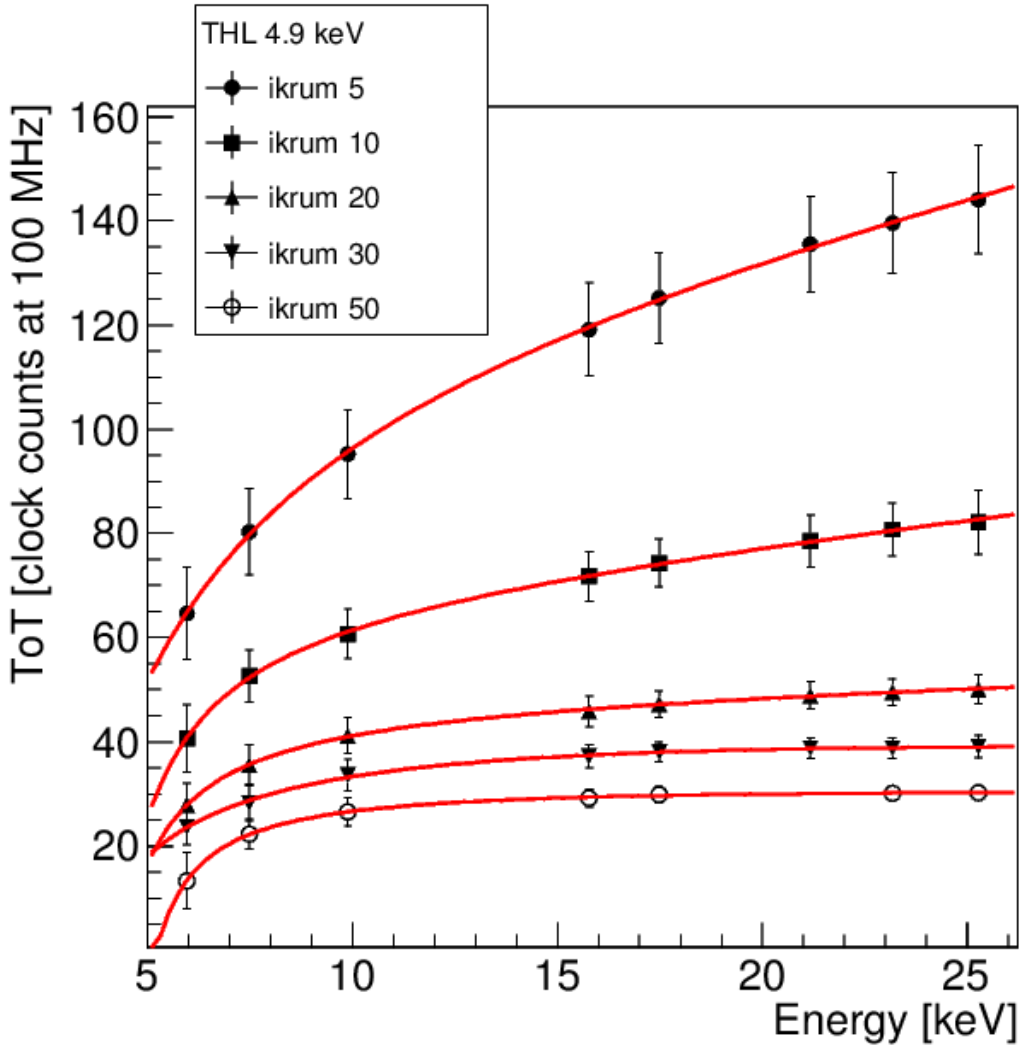


Charge sharing



Si absorption curve

Timepix calibration



Calibration of the Timepix energy scale
~ roughly 1 week of work

Single threshold vs energy window

$$\begin{cases} N_{l,\theta,t_1} = \int_{t_1}^{+\infty} \ldots e^{\cdots} \\ N_{l,\theta,t_2} = \int_{t_2}^{+\infty} \ldots e^{\cdots} \end{cases}$$

Single threshold vs energy window

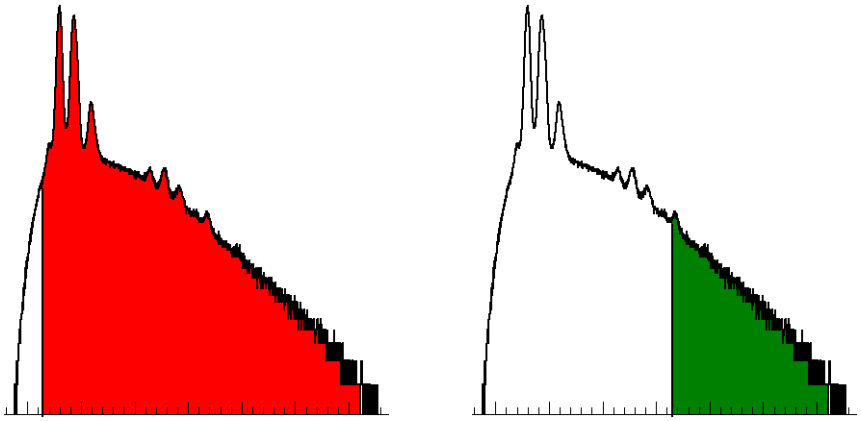
$$\begin{cases} N_{l,\theta,t_1} = \int_{t_1}^{+\infty} \ldots e^{\cdots} \\ N_{l,\theta,t_2} = \int_{t_2}^{+\infty} \ldots e^{\cdots} \end{cases}$$

$$\begin{cases} N_{l,\theta,t_{12}} = \int_{t_1}^{t_2} \ldots e^{\cdots} \\ N_{l,\theta,t_{23}} = \int_{t_2}^{t_3} \ldots e^{\cdots} \end{cases}$$

Single threshold vs energy window

$$\begin{cases} N_{l,\theta,t_1} = \int_{t_1}^{+\infty} \dots e^{\cdots} \\ N_{l,\theta,t_2} = \int_{t_2}^{+\infty} \dots e^{\cdots} \end{cases}$$

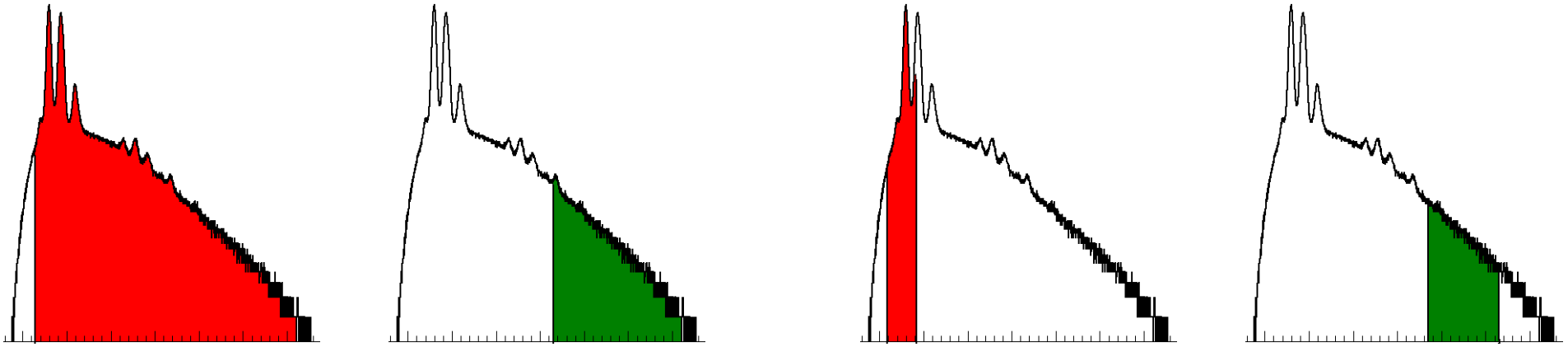
$$\begin{cases} N_{l,\theta,t_{12}} = \int_{t_1}^{t_2} \dots e^{\cdots} \\ N_{l,\theta,t_{23}} = \int_{t_2}^{t_3} \dots e^{\cdots} \end{cases}$$



Single threshold vs energy window

$$\begin{cases} N_{l,\theta,t_1} = \int_{t_1}^{+\infty} \ldots e^{\cdots} \\ N_{l,\theta,t_2} = \int_{t_2}^{+\infty} \ldots e^{\cdots} \end{cases}$$

$$\begin{cases} N_{l,\theta,t_{12}} = \int_{t_1}^{t_2} \ldots e^{\cdots} \\ N_{l,\theta,t_{23}} = \int_{t_2}^{t_3} \ldots e^{\cdots} \end{cases}$$



$$I_{l,\theta} = I_0 e^{-\int_{l,\theta} \mu(s)\,ds} \Rightarrow \int_{l,\theta} \mu(s)\,ds = -\log \frac{I_{l,\theta}}{I_0}$$

Linear system!

$$I_{l,\theta}(E) = I_0(E)\, e^{-\int_{l,\theta} \mu(s,E)\,ds}$$

$$I_{l,\theta} = I_0 e^{-\int_{l,\theta} \mu(s)\,ds} \Rightarrow \int_{l,\theta} \mu(s)\,ds = -\log \frac{I_{l,\theta}}{I_0}$$

Linear system!

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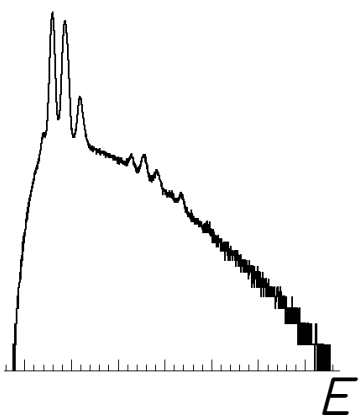

$$I_{l,\theta} = I_0 e^{-\int_{l,\theta} \mu(s)\,ds} \Rightarrow \int_{l,\theta} \mu(s)\,ds = -\log \frac{I_{l,\theta}}{I_0}$$

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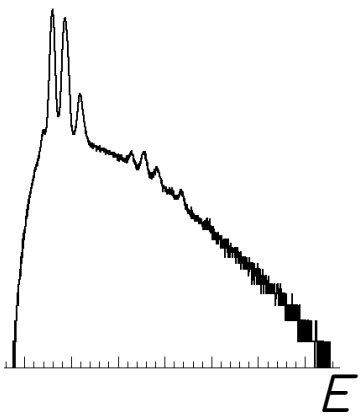

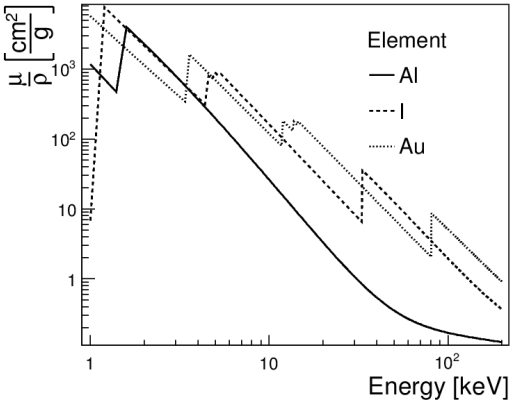

$$I_{l,\theta} = I_0 e^{-\int_{l,\theta} \mu(s)\,ds} \quad \Rightarrow \quad \int_{l,\theta} \mu(s)\,ds = -\log \frac{I_{l,\theta}}{I_0}$$

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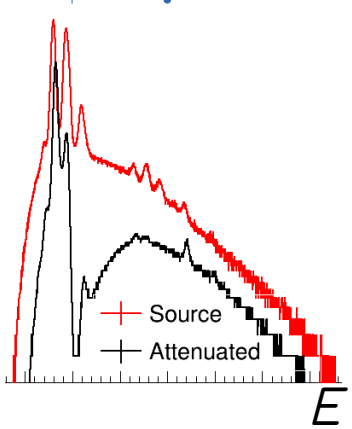
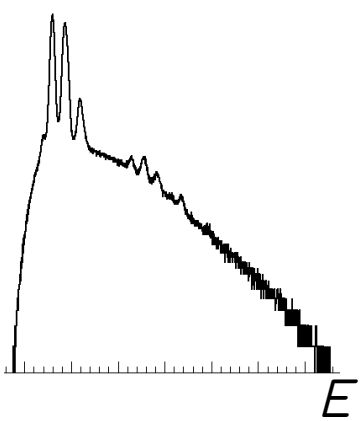
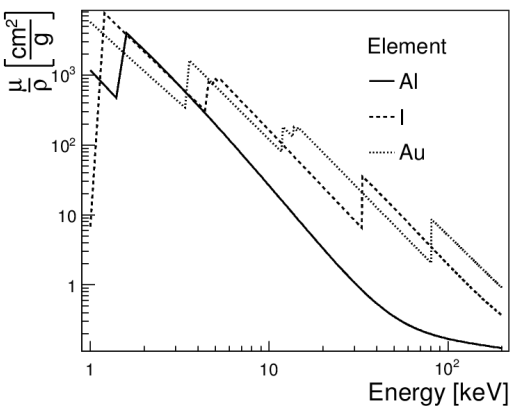






$$I_{l,\theta} = I_0 e^{-\int_{l,\theta} \mu(s)\,ds}$$

$$\int_{l,\theta} \mu(s)\,ds = -\log \frac{I_{l,\theta}}{I_0}$$

Linear system!

$$I_{l,\theta}(E) = I_0(E)\, e^{-\int_{l,\theta} \mu(s,E)\,ds}$$

Still doable, BUT...

$$I_{l,\theta} = I_0 e^{-\int_{l,\theta} \mu(s)\,ds}$$

$$\int_{l,\theta} \mu(s)\,ds = -\log \frac{I_{l,\theta}}{I_0}$$

Linear system!

$$\boxed{I_{l,\theta}(E)} = I_0(E)\, e^{-\int_{l,\theta} \mu(s,E)\,ds}$$

Still doable, BUT...

$$N_{l,\theta} = \int_0^{+\infty} dE\, \boxed{I_{l,\theta}(E)}$$

$$I_{l,\theta} = I_0 e^{-\int_{l,\theta} \mu(s)\,ds}$$

$$\int_{l,\theta} \mu(s)\,ds = -\log \frac{I_{l,\theta}}{I_0}$$

Linear system!

$$I_{l,\theta}(E) = \boxed{I_0(E)\, e^{-\int_{l,\theta} \mu(s,E)\,ds}}$$

Still doable, BUT...

$$N_{l,\theta} = \int_0^{+\infty} dE\, I_{l,\theta}(E)$$

$$N_{l,\theta} = \int_0^{+\infty} dE\, \boxed{I_0(E)\, e^{-\int_{l,\theta} \mu(s,E)\,ds}}$$

$$I_{l,\theta} = I_0 e^{-\int_{l,\theta} \mu(s)\,ds}$$

$$\int_{l,\theta} \mu(s)\,ds = -\log \frac{I_{l,\theta}}{I_0}$$

Linear system!

$$I_{l,\theta}(E) = \boxed{I_0(E)\, e^{-\int_{l,\theta} \mu(s,E)\,ds}}$$

Still doable, BUT...

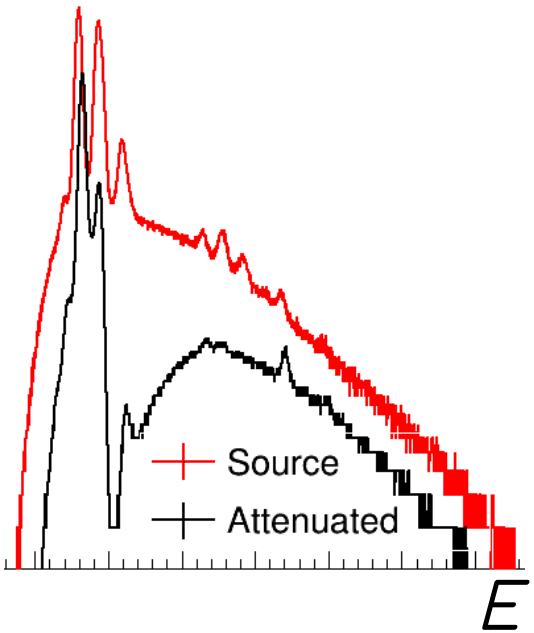
$$N_{l,\theta} = \int_0^{+\infty} dE\, I_{l,\theta}(E)$$

$$N_{l,\theta} = \int_0^{+\infty} dE\, \boxed{I_0(E)\, e^{-\int_{l,\theta} \mu(s,E)\,ds}}$$

$$N_{l,\theta} = \int_0^{+\infty} dE \underbrace{I_0(E)\, e^{-\int_{l,\theta} \mu(s,E)\, ds}}_{I(E)}$$

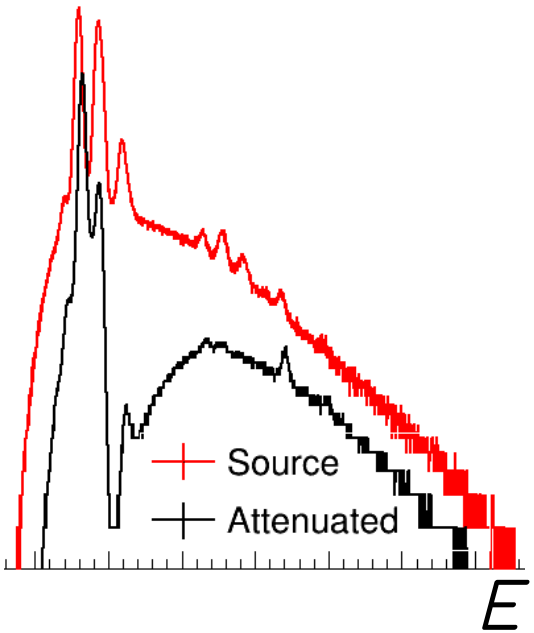
$$N_{l,\theta} = \int_0^{+\infty} dE \underbrace{I_0(E)\, e^{-\int_{l,\theta} \mu(s,E)\, ds}}_{I(E)}$$

A tube spectrum after transmission through the sample

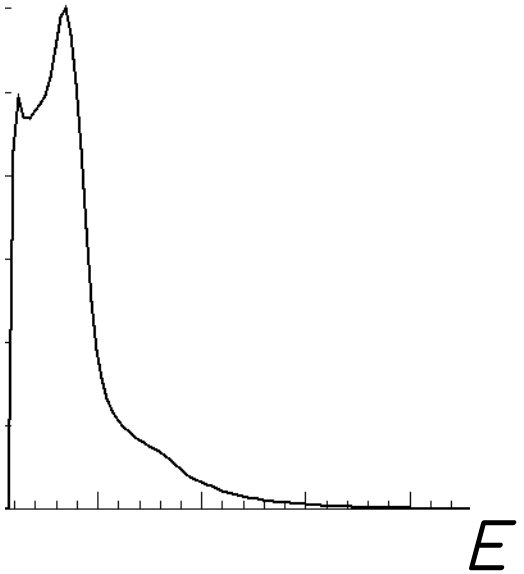


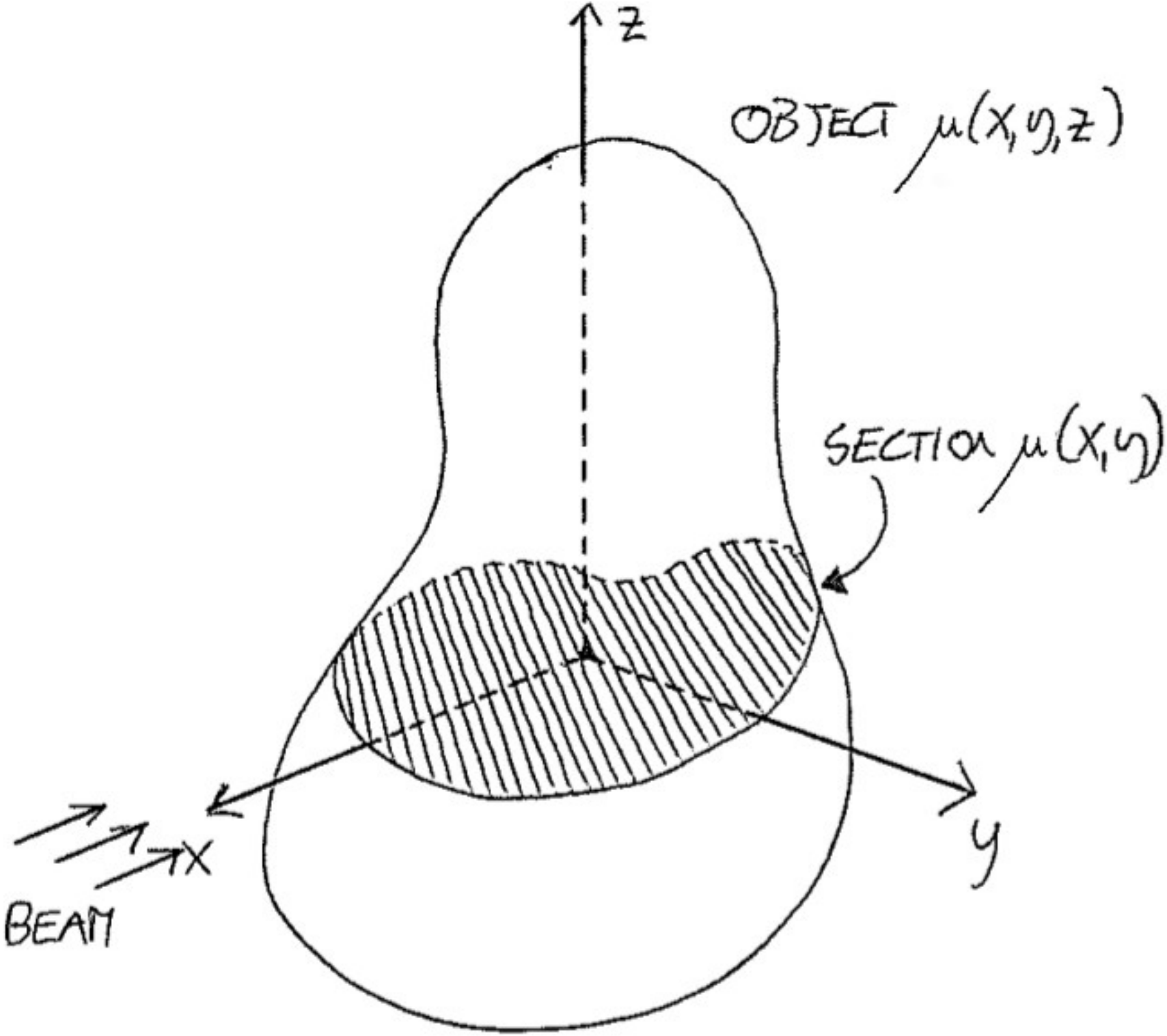
$$N_{l,\theta} = \int_0^{+\infty} dE \underbrace{I_0(E)\, e^{-\int_{l,\theta} \mu(s,E)\,ds}}_{I(E)}$$

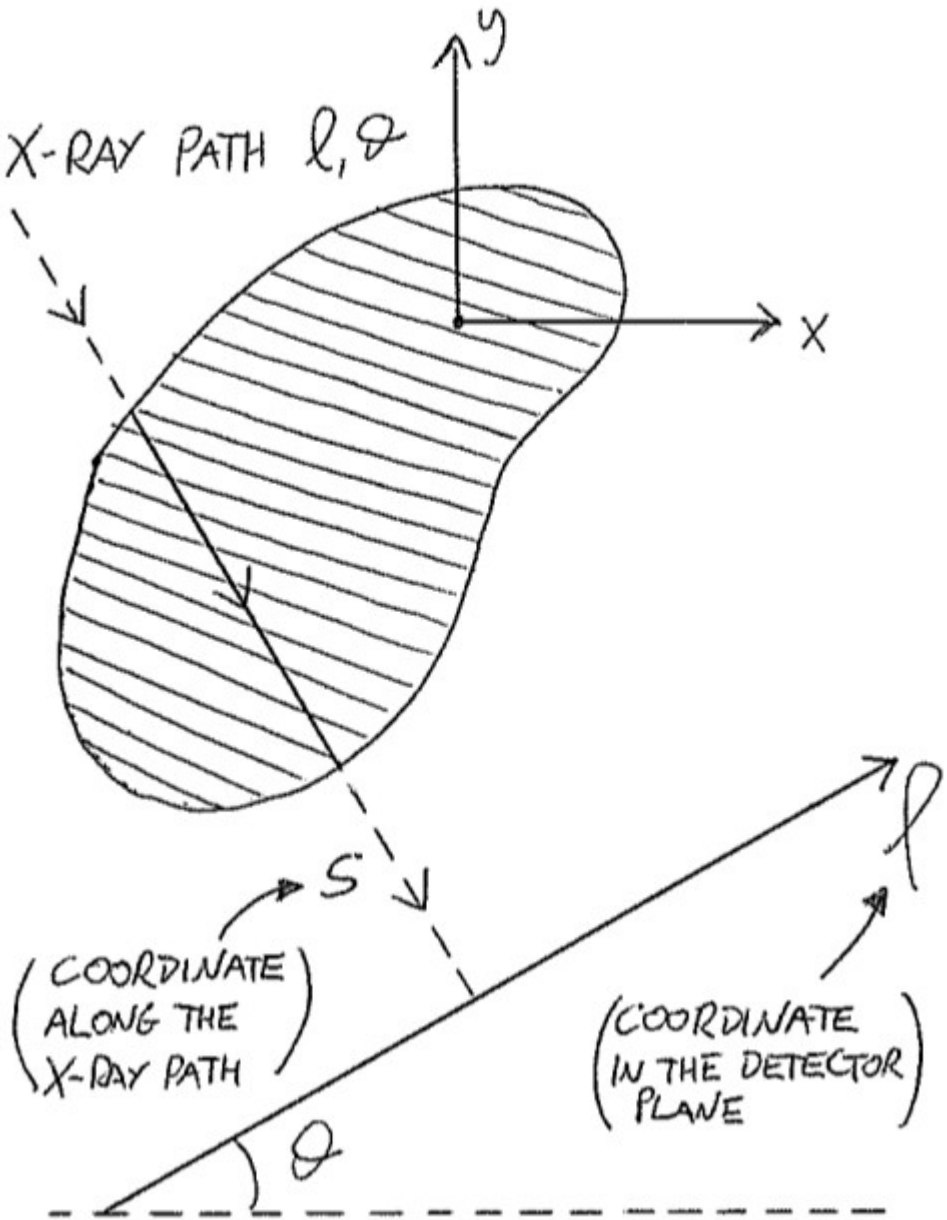
A tube spectrum after transmission through the sample

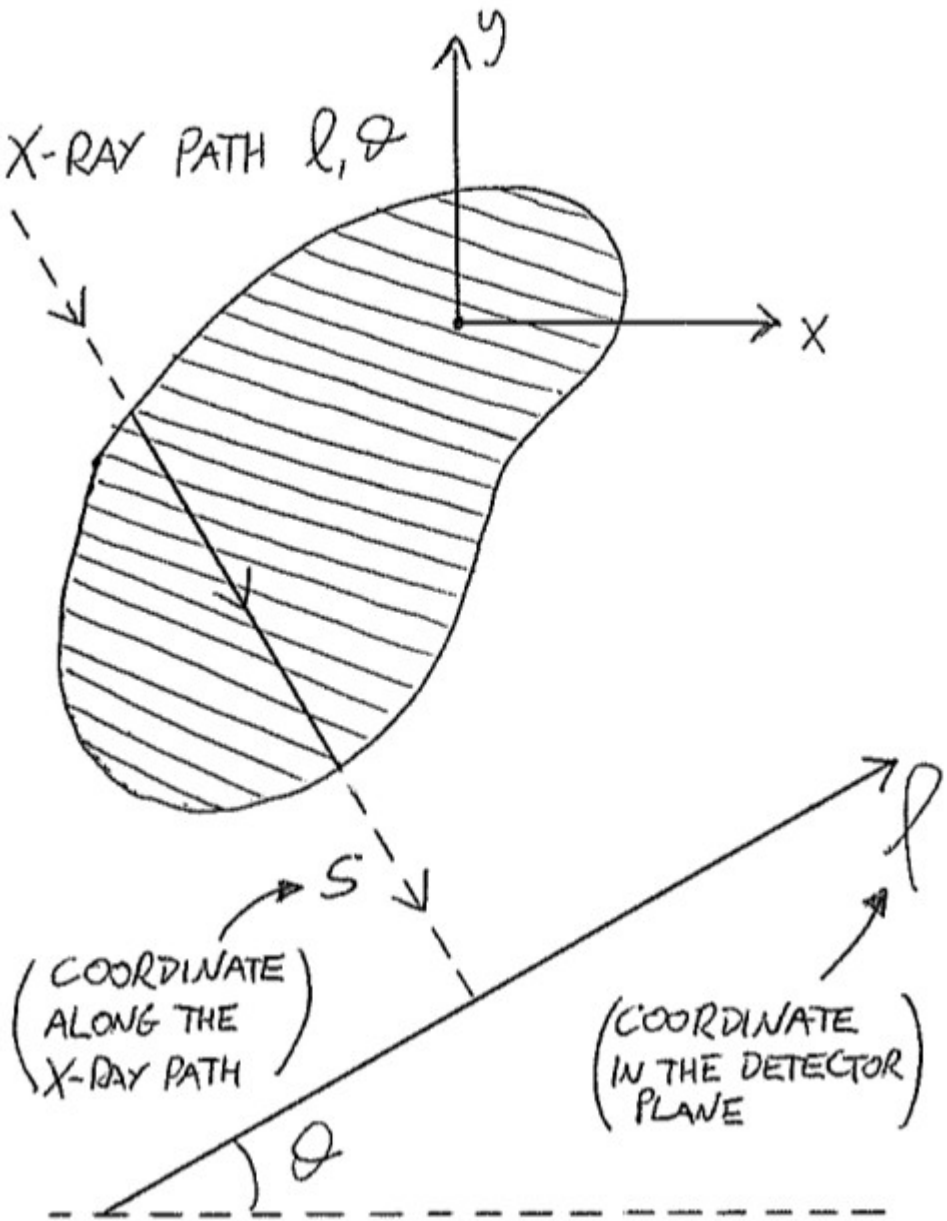


A tube spectrum as seen by a Medipix2-based silicon detector

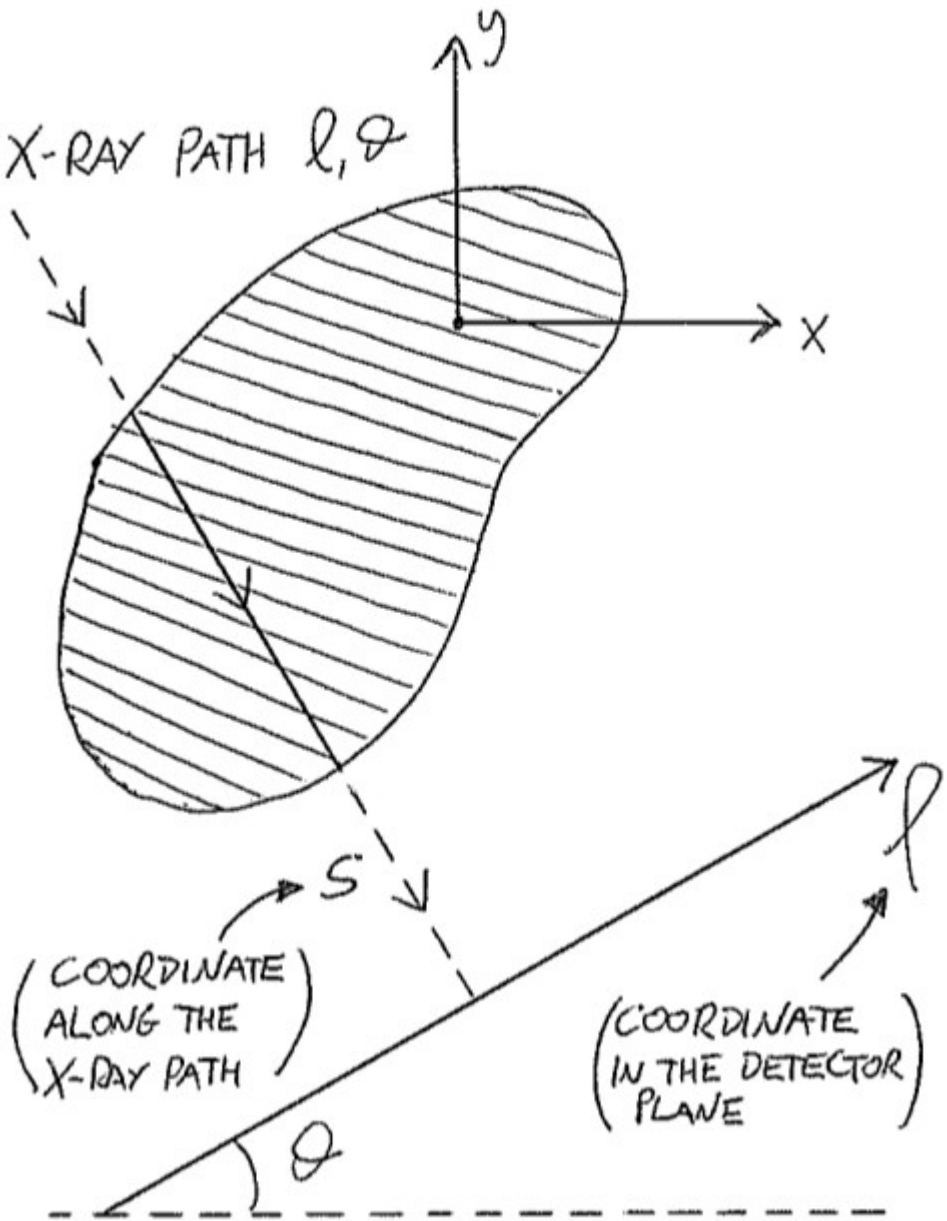



z
OBJECT μ(x,y,z)
SECTION μ(x,y)
x
y
BEAM


y
X-RAY PATH ℓ, θ
x
s
ρ
(COORDINATE ALONG THE X-RAY PATH)
(COORDINATE IN THE DETECTOR PLANE)
θ



$$I_{l,\theta} = I_0 e^{-\int_{l,\theta} \mu(s)\,ds}$$



$$I_{l,\theta} = I_0 e^{-\int_{l,\theta} \mu(s)\,ds}$$

$$\int_{l,\theta} \mu(s)\,ds = -\log \frac{I_{l,\theta}}{I_0}$$

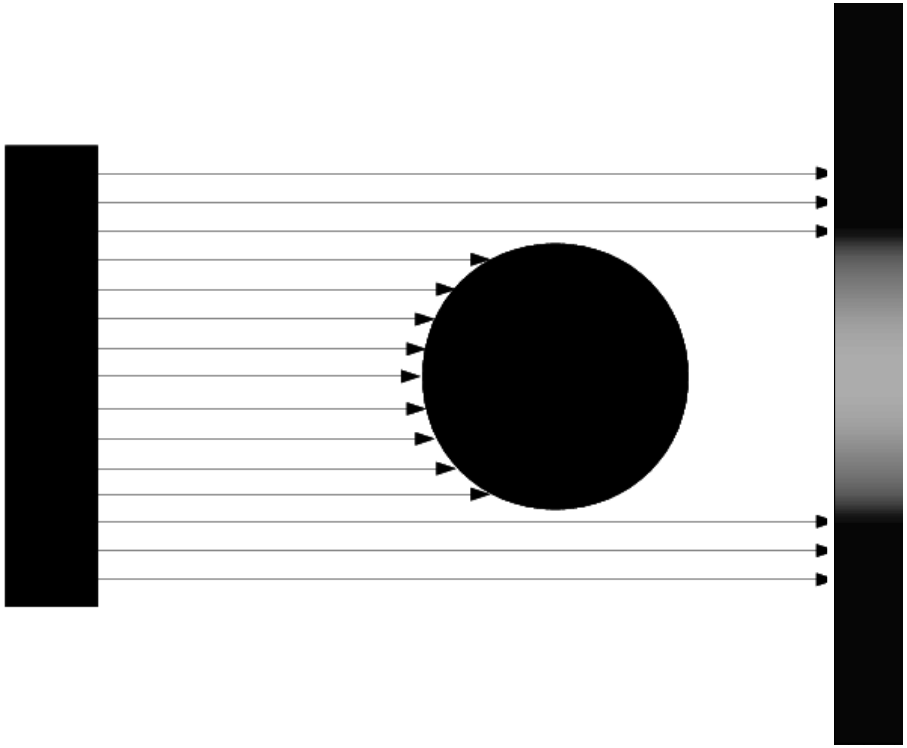
A linear system, can you see it?

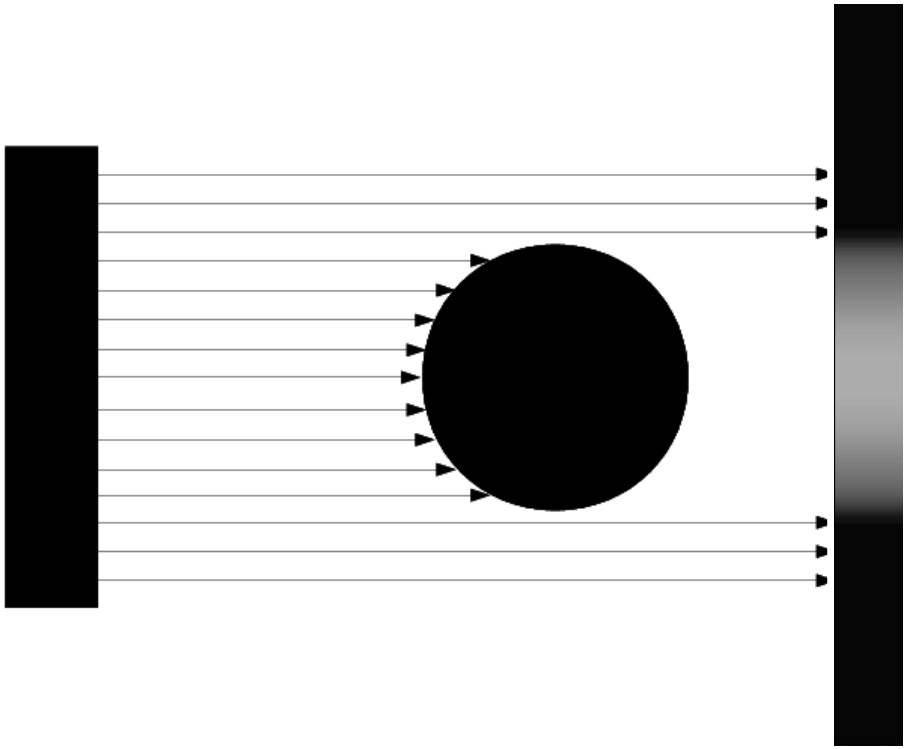
PIXEL = PIcture ELement

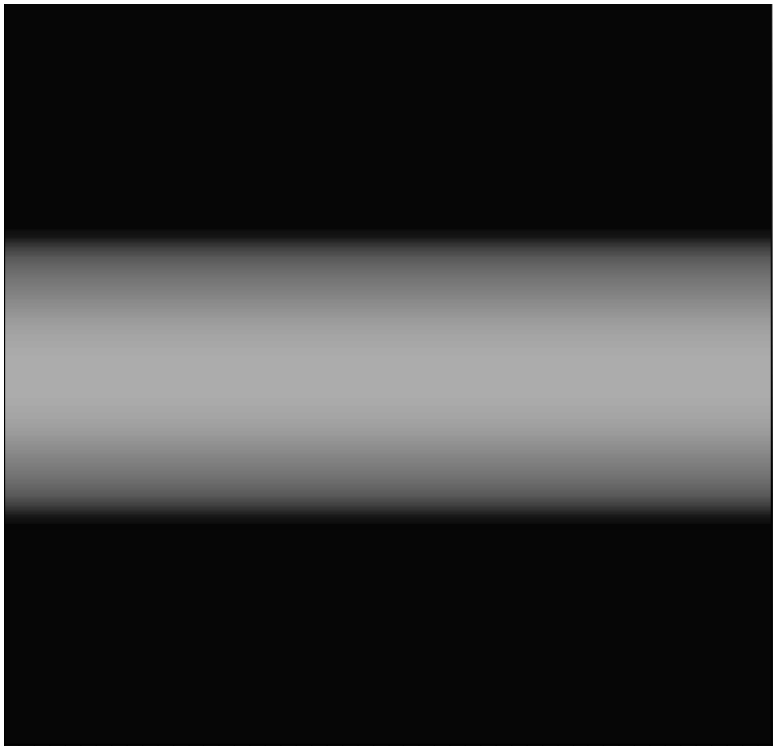
→ *detector*

VOXEL = 3D pixel

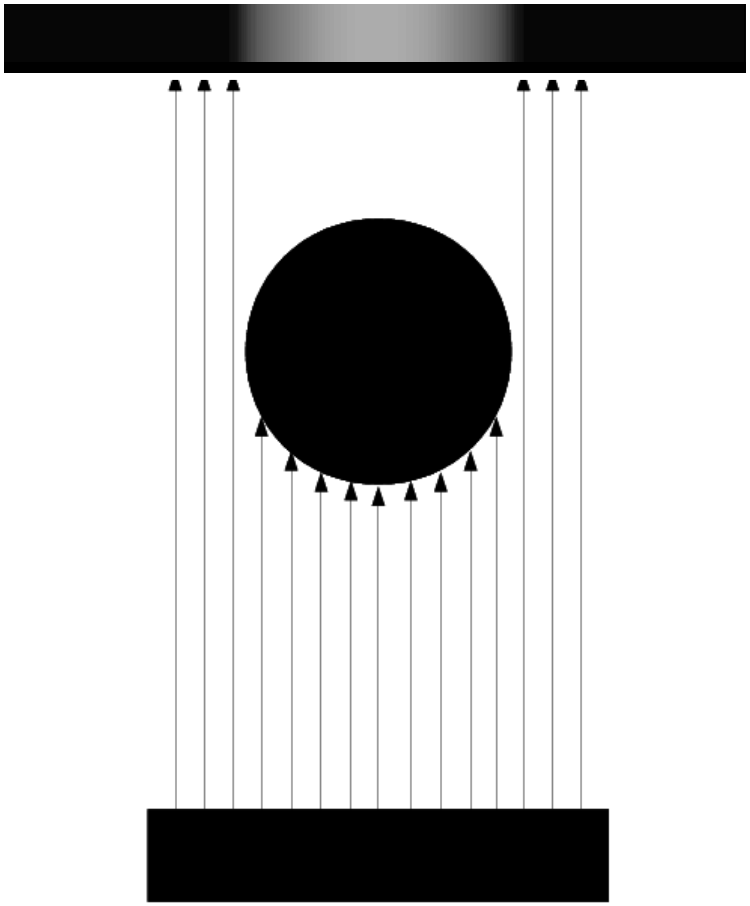
→ *image*

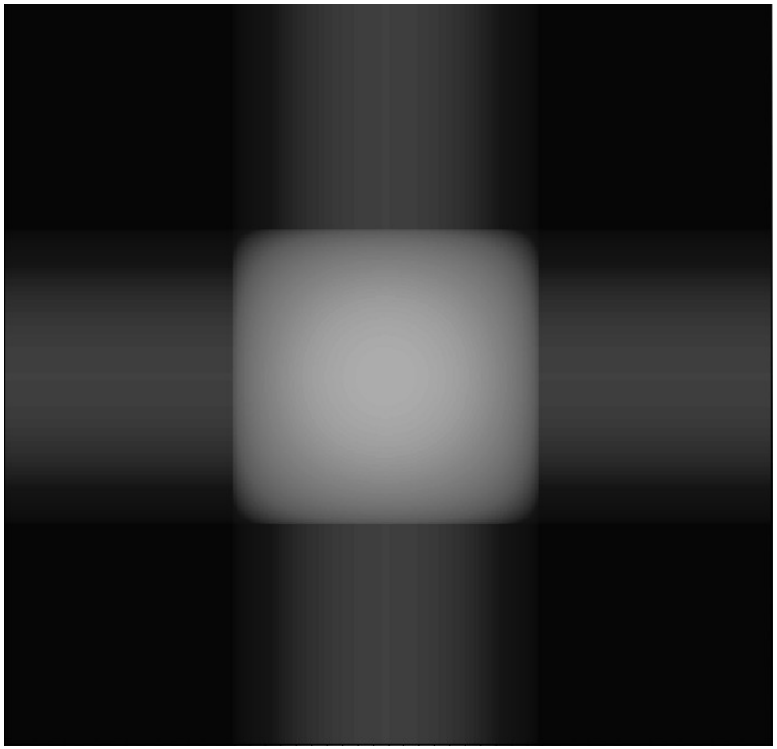




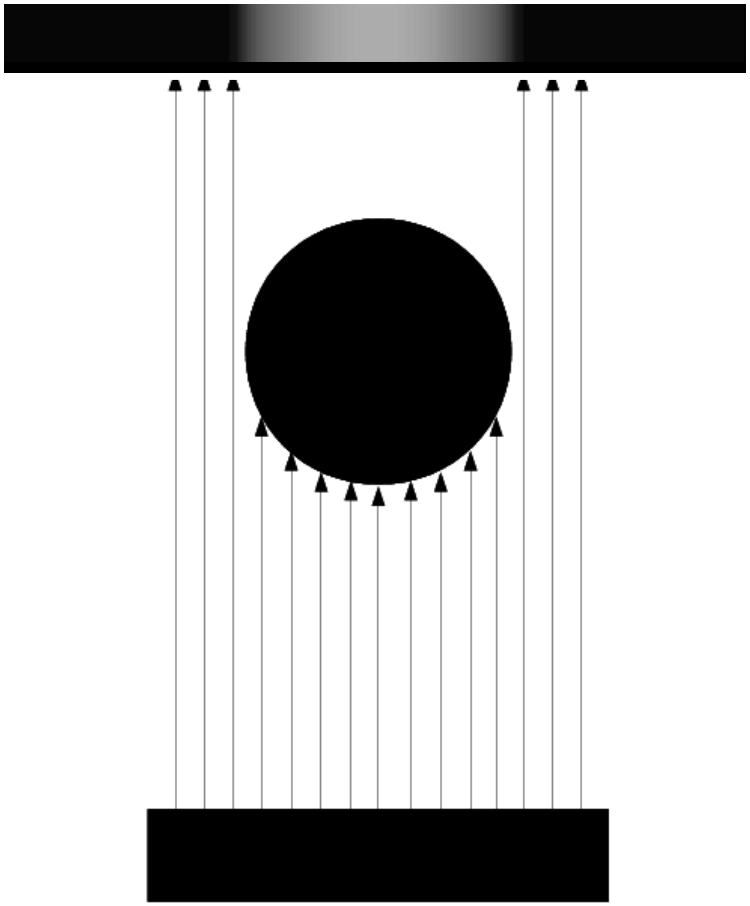


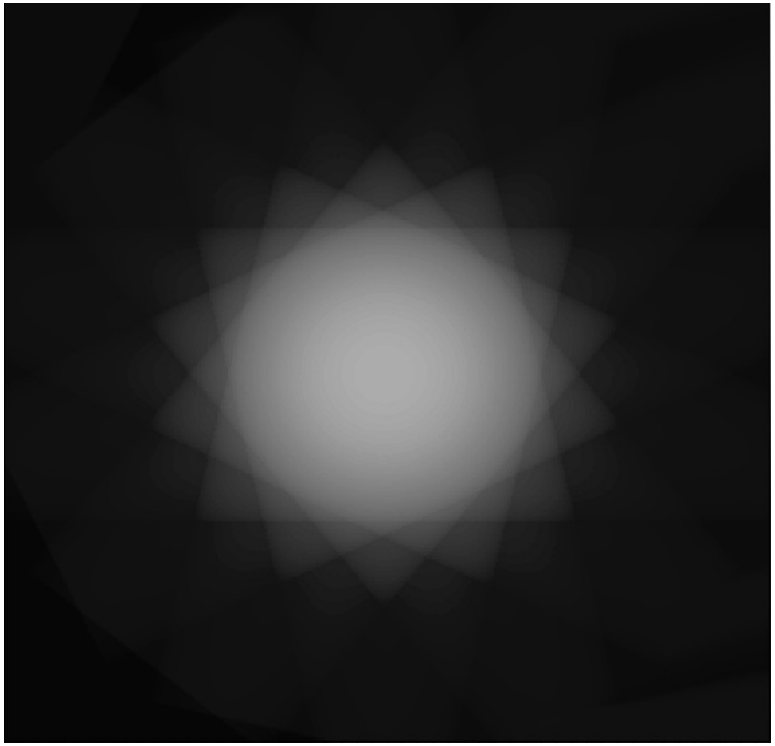
backprojection





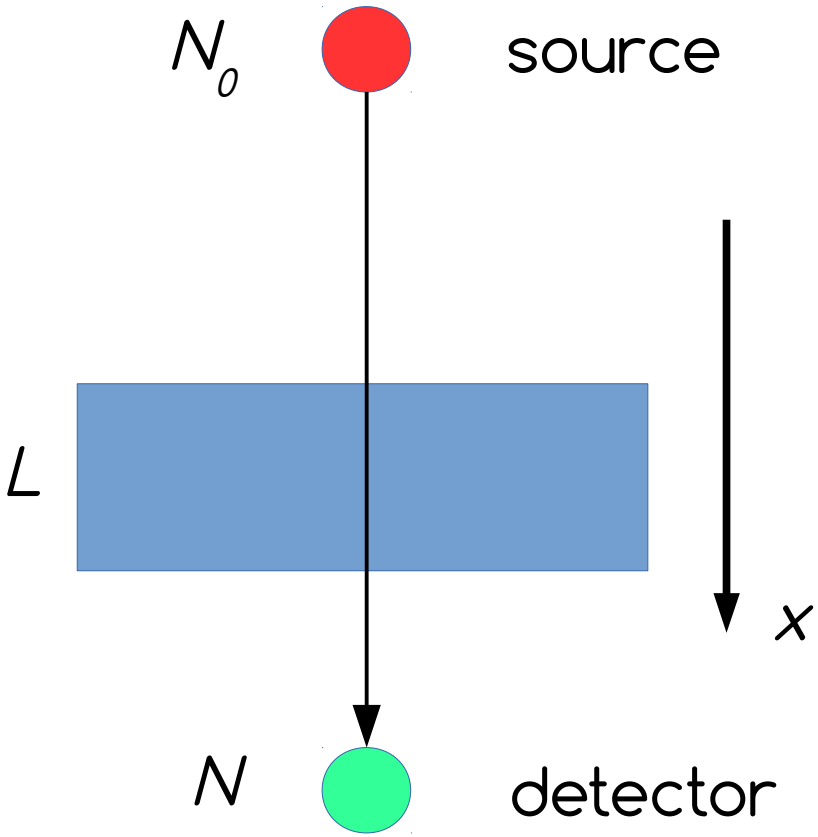
backprojection

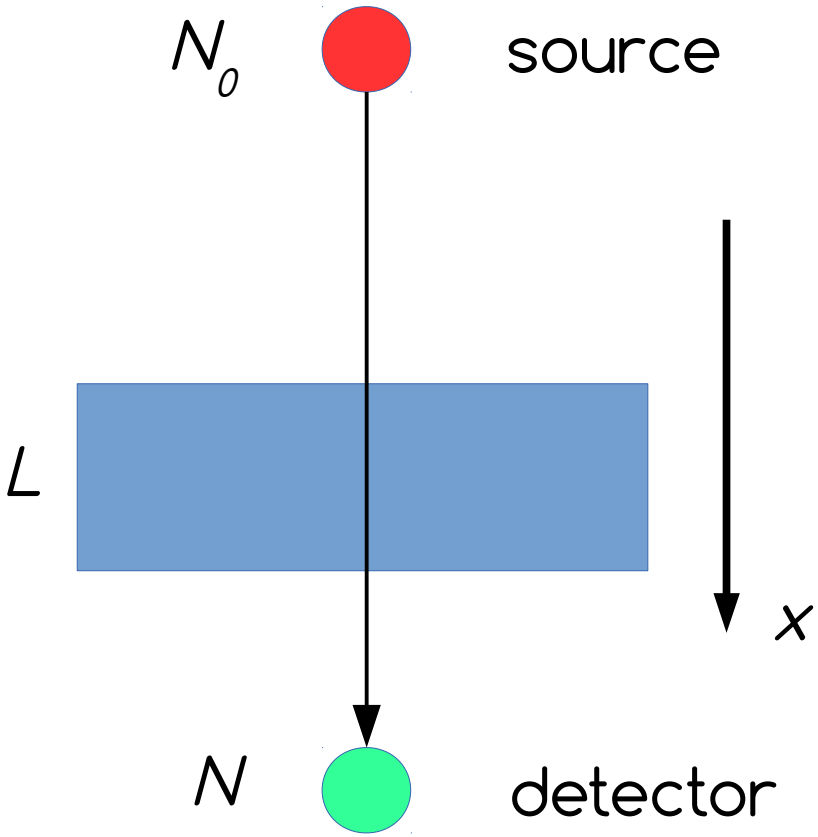




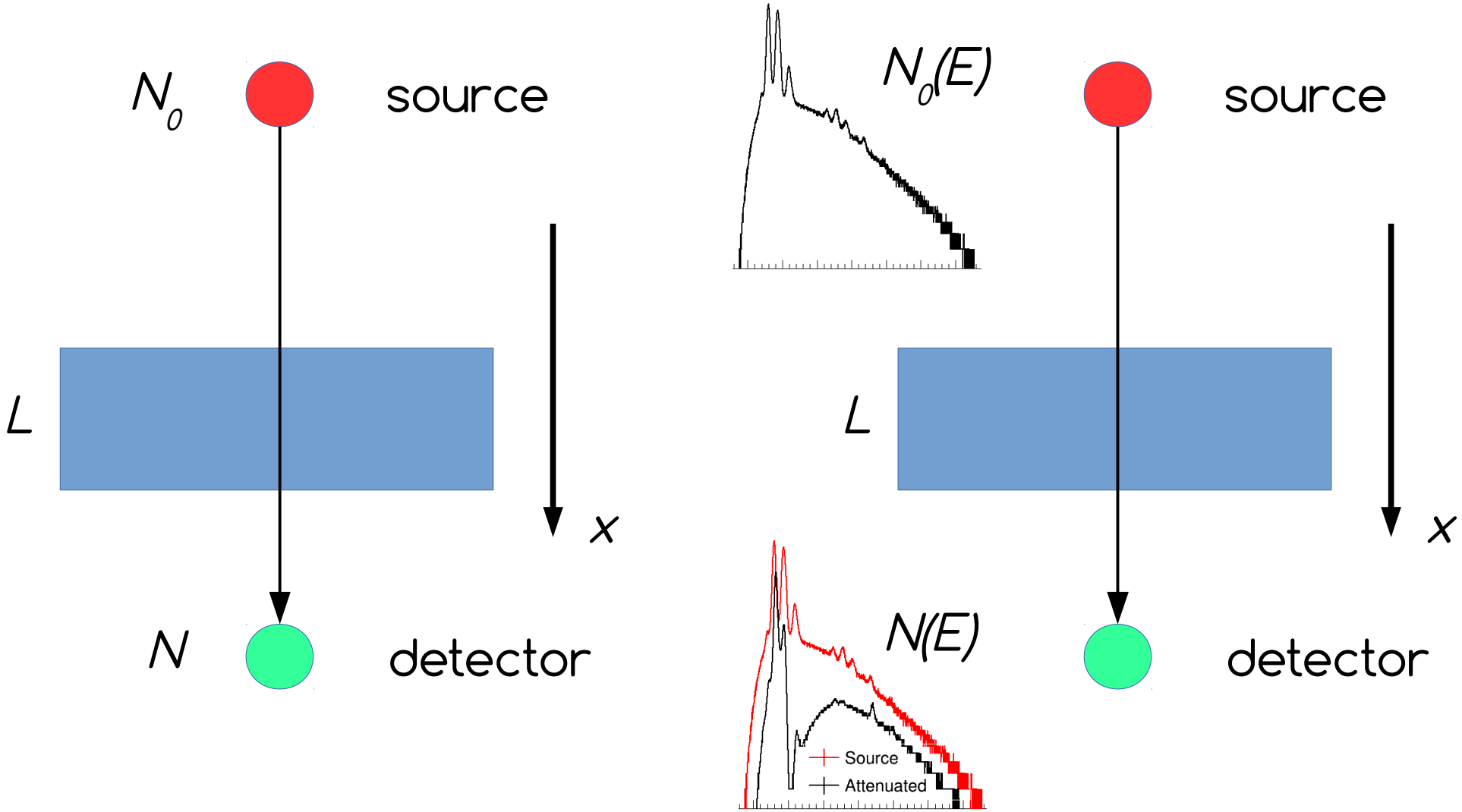
backprojection

RULE #5 (the most important!):
NEW RECONSTRUCTION ALGORITHM

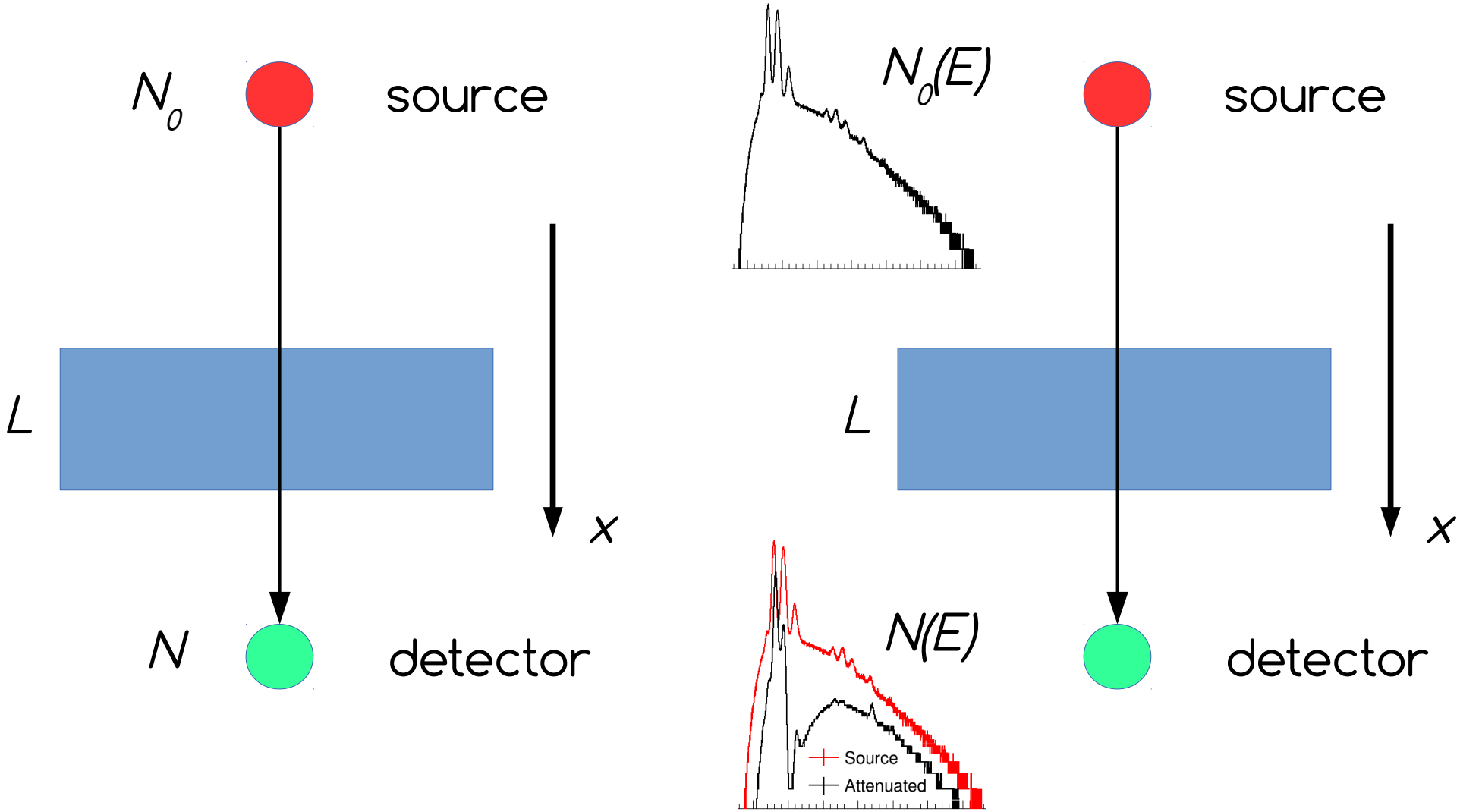

N_0
source
L
x
N
detector



$$N = N_0 e^{-\int_L \mu(x)\,dx}$$

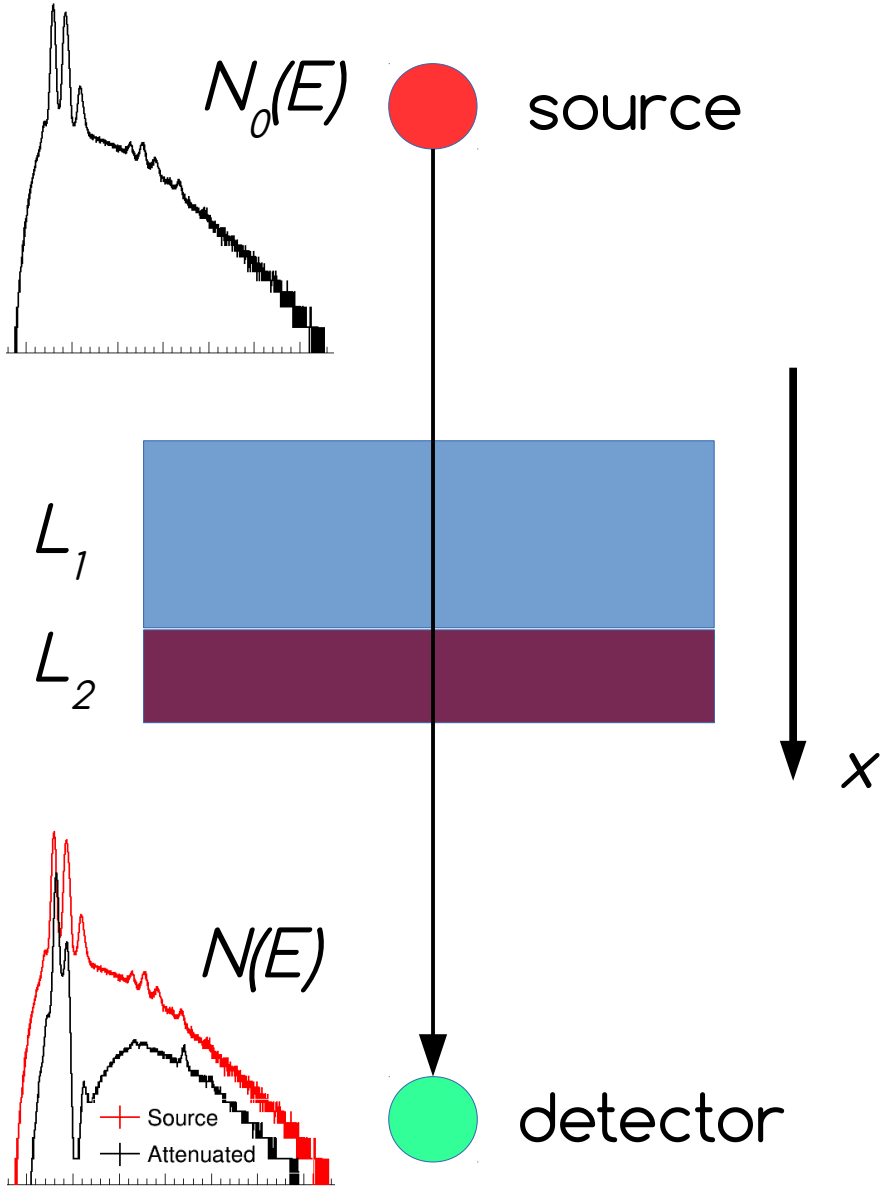


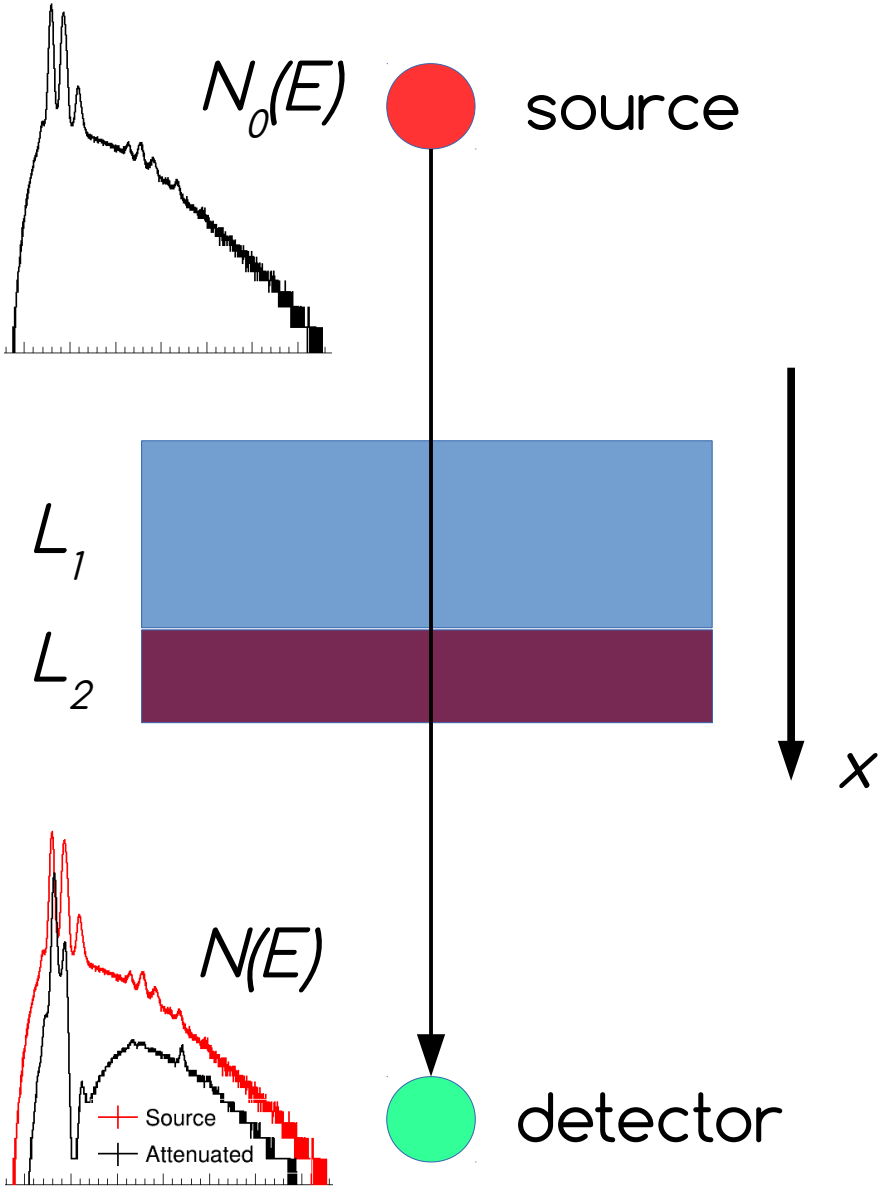
$$N = N_0 e^{-\int_L \mu(x)\,dx}$$



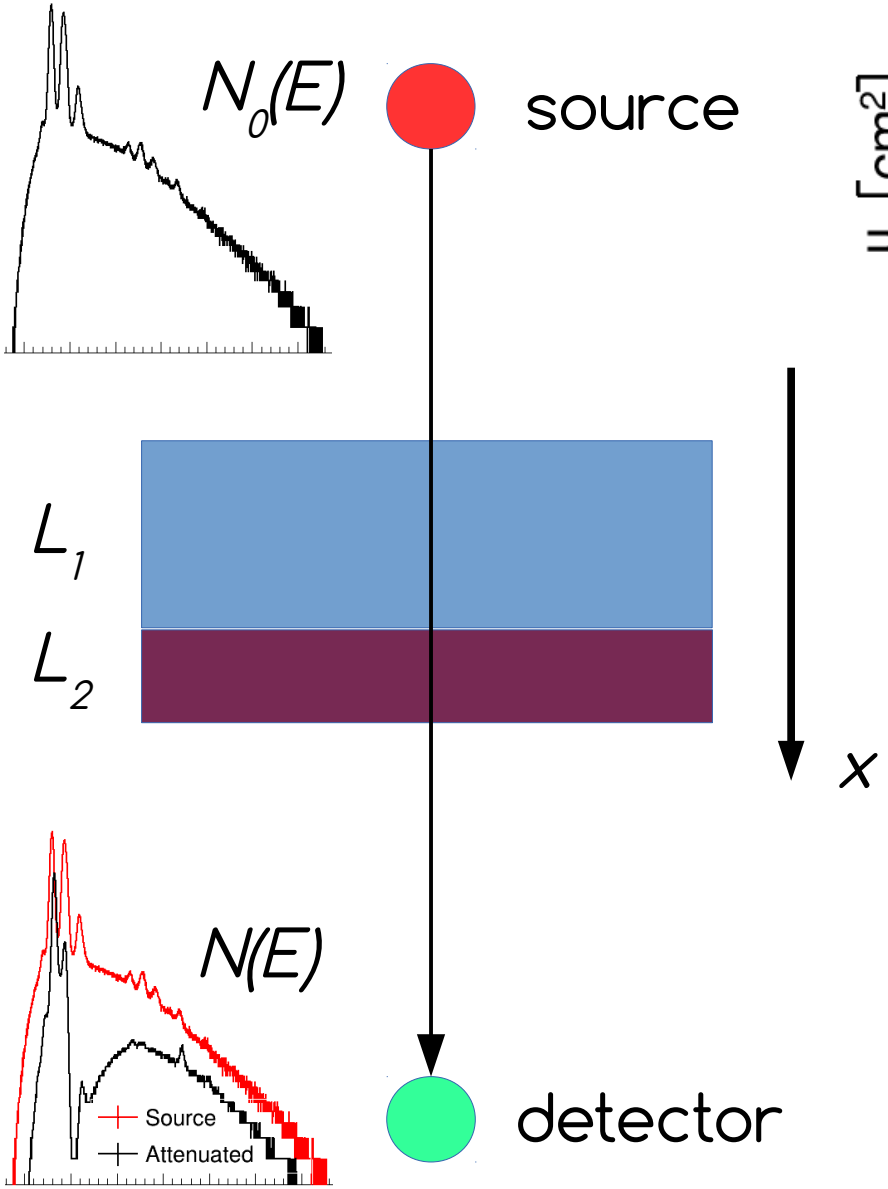
$$N = N_0 e^{-\int_L \mu(x)\,dx}$$

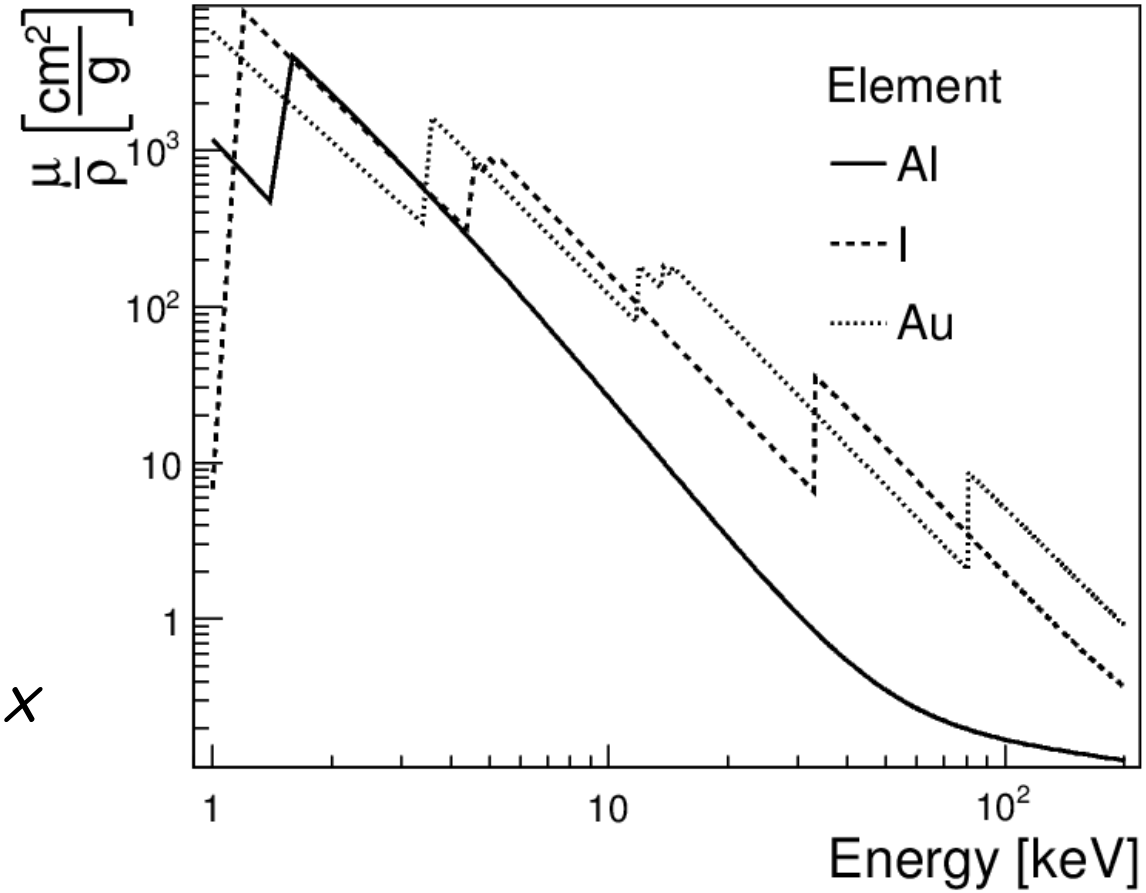
$$N(E) = N_0(E)\, e^{-\int_L \mu(x,E)\,dx}$$


$N_0(E)$
source
L_1
L_2
x
$N(E)$
Source
Attenuated
detector

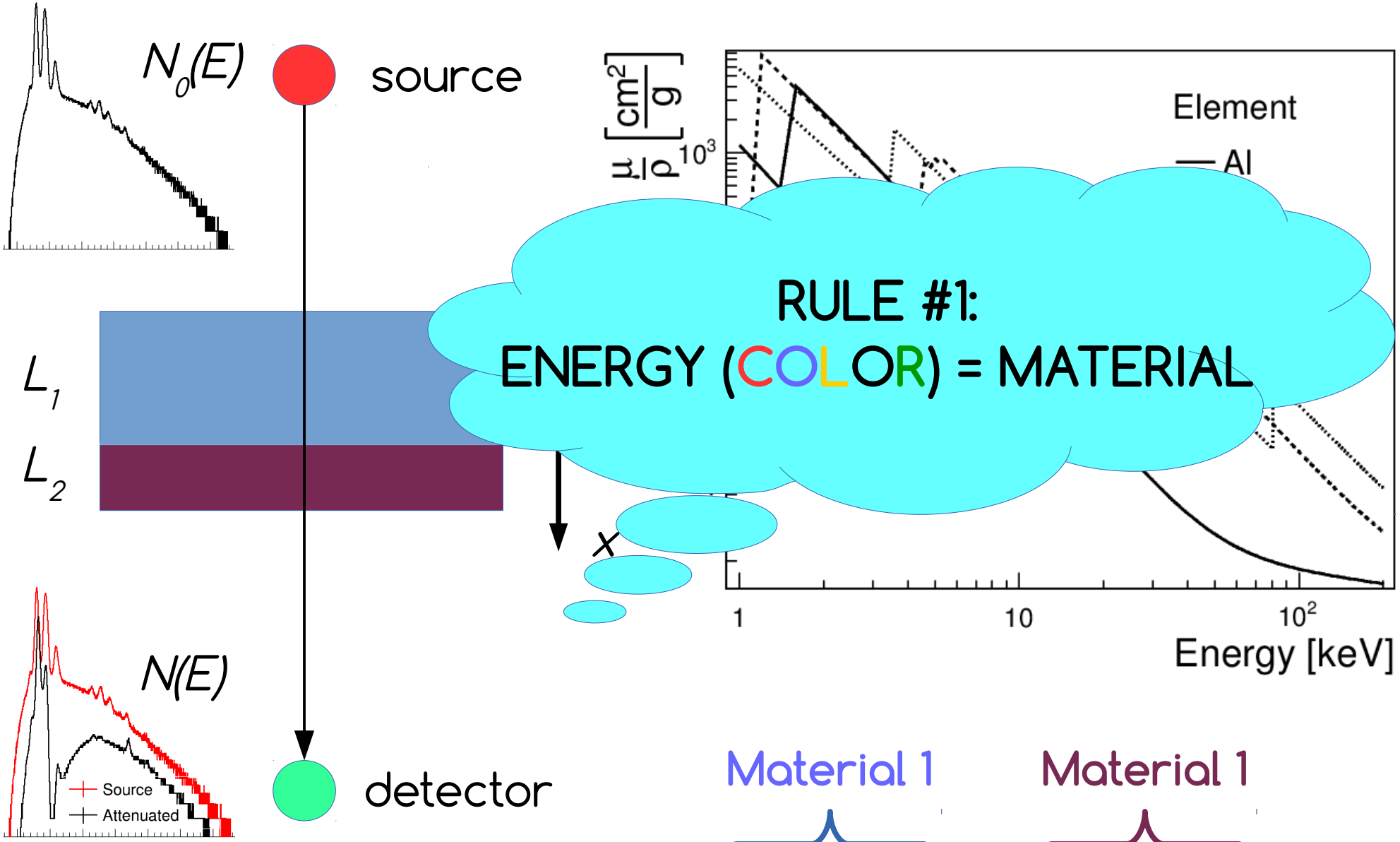


$$N(E) = N_0(E)\, e^{-\overbrace{\int_{L_1} \mu_1(x,E)\,dx}^{\text{Material 1}} - \overbrace{\int_{L_2} \mu_2(x,E)\,dx}^{\text{Material 1}}}$$

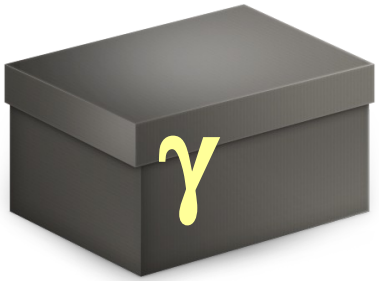


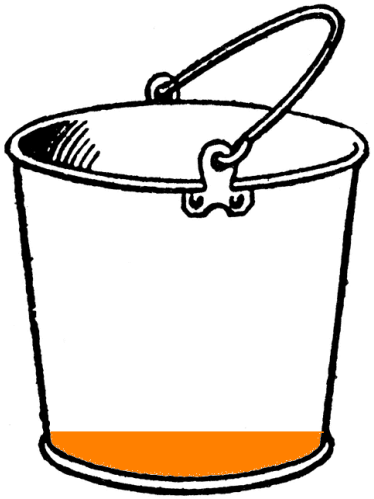


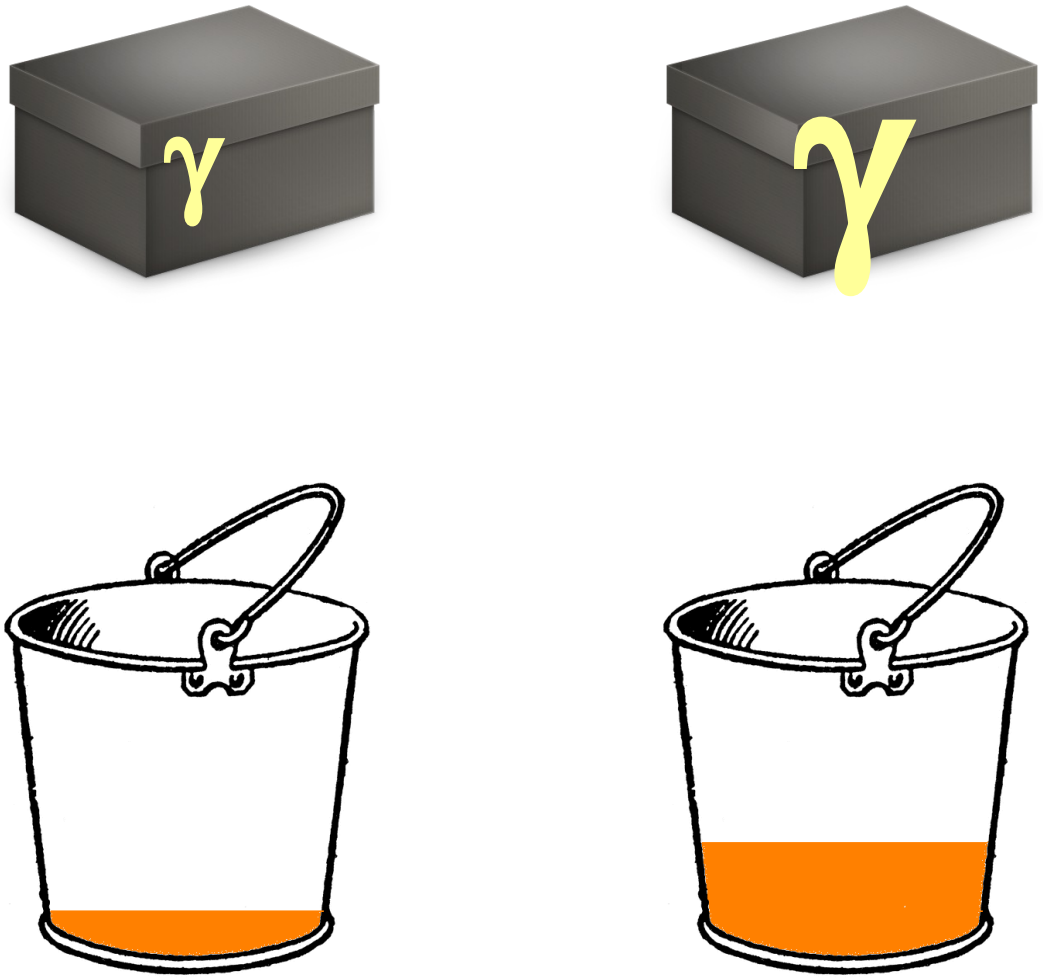
$$N(E)=N_0(E)\,e^{-\overbrace{\int_{L_1}\mu_1(x,E)\,dx}^{\text{Material 1}}-\overbrace{\int_{L_2}\mu_2(x,E)\,dx}^{\text{Material 1}}}$$



$$N(E)=N_0(E)\,e^{-\overbrace{\int_{L_1}\mu_1(x,E)\,dx}^{\text{Material 1}}-\overbrace{\int_{L_2}\mu_2(x,E)\,dx}^{\text{Material 1}}}$$

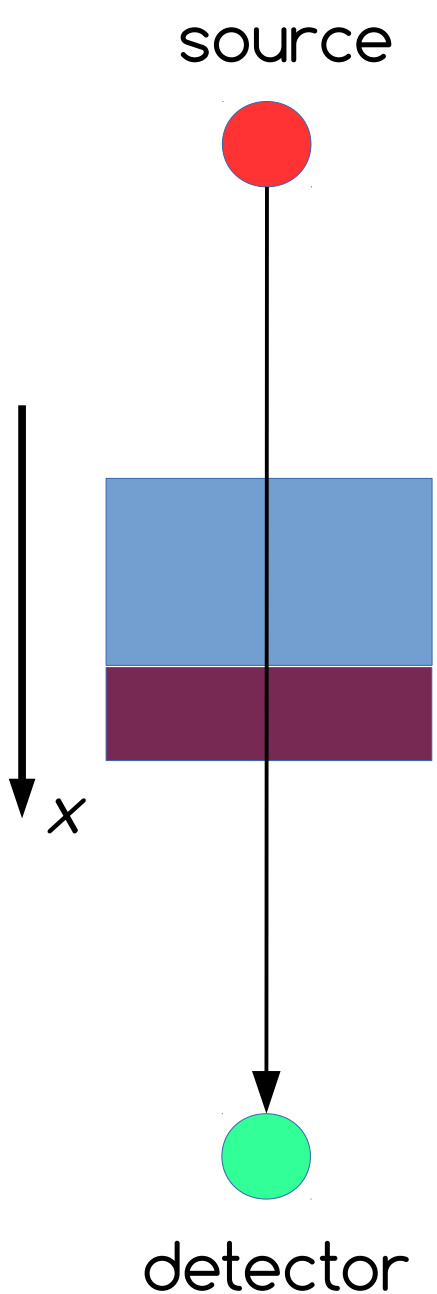

γ

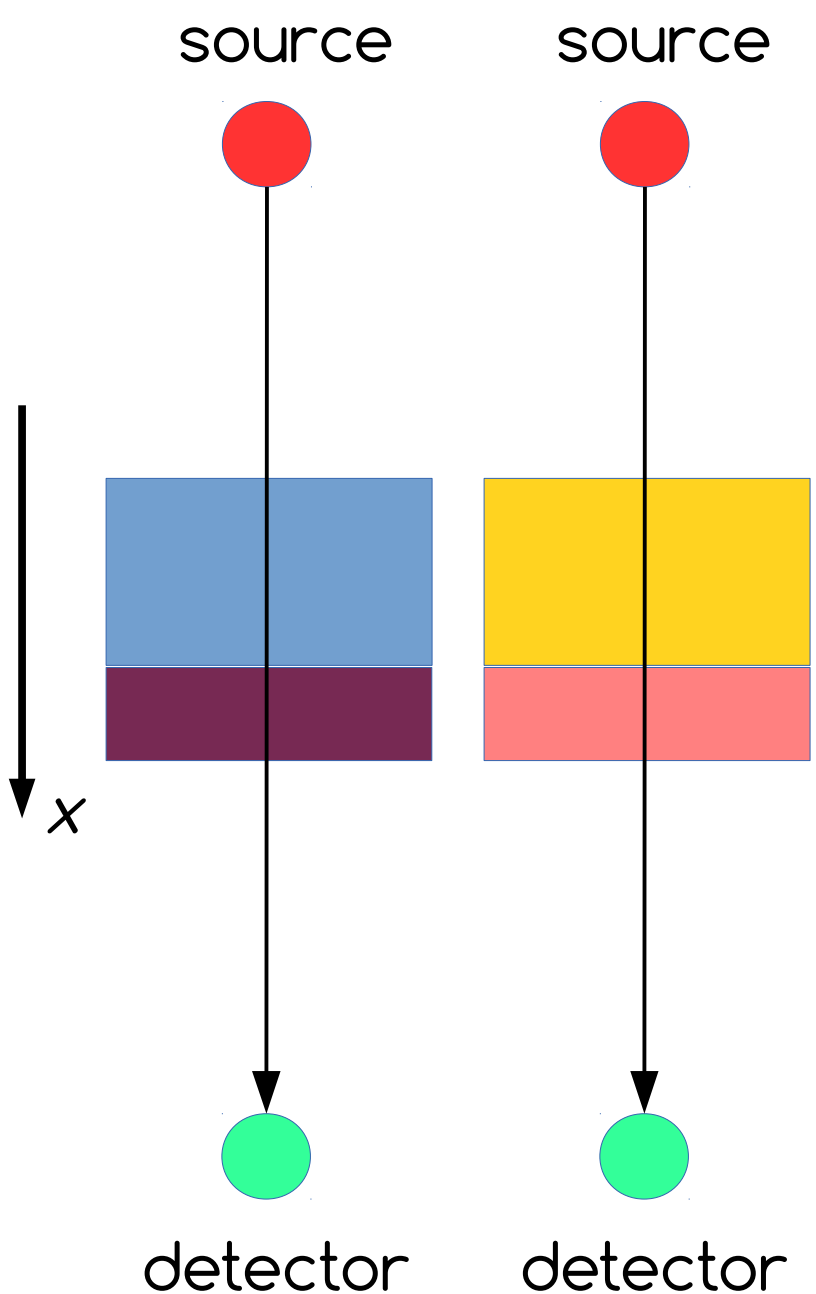


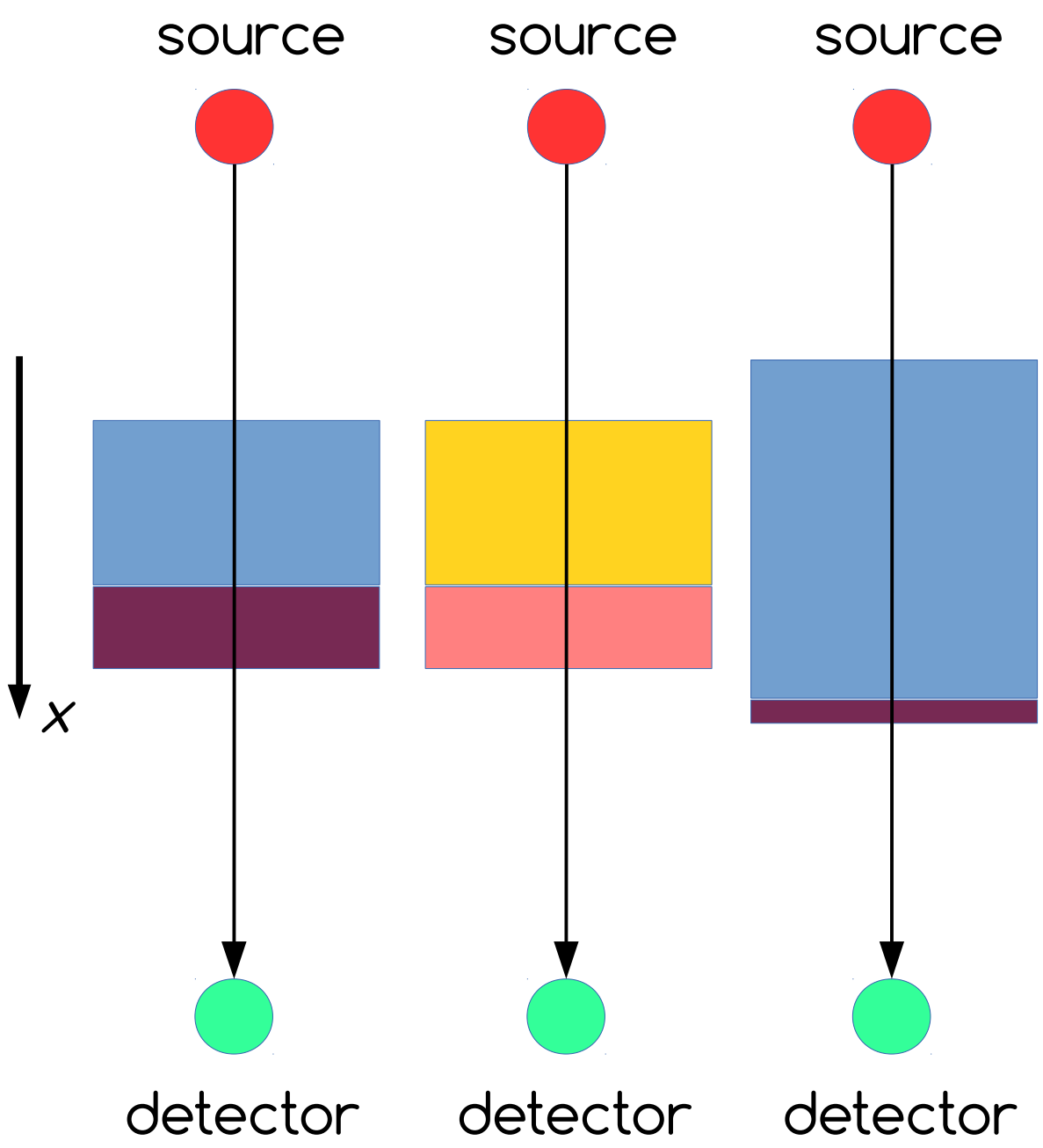

γ
γ

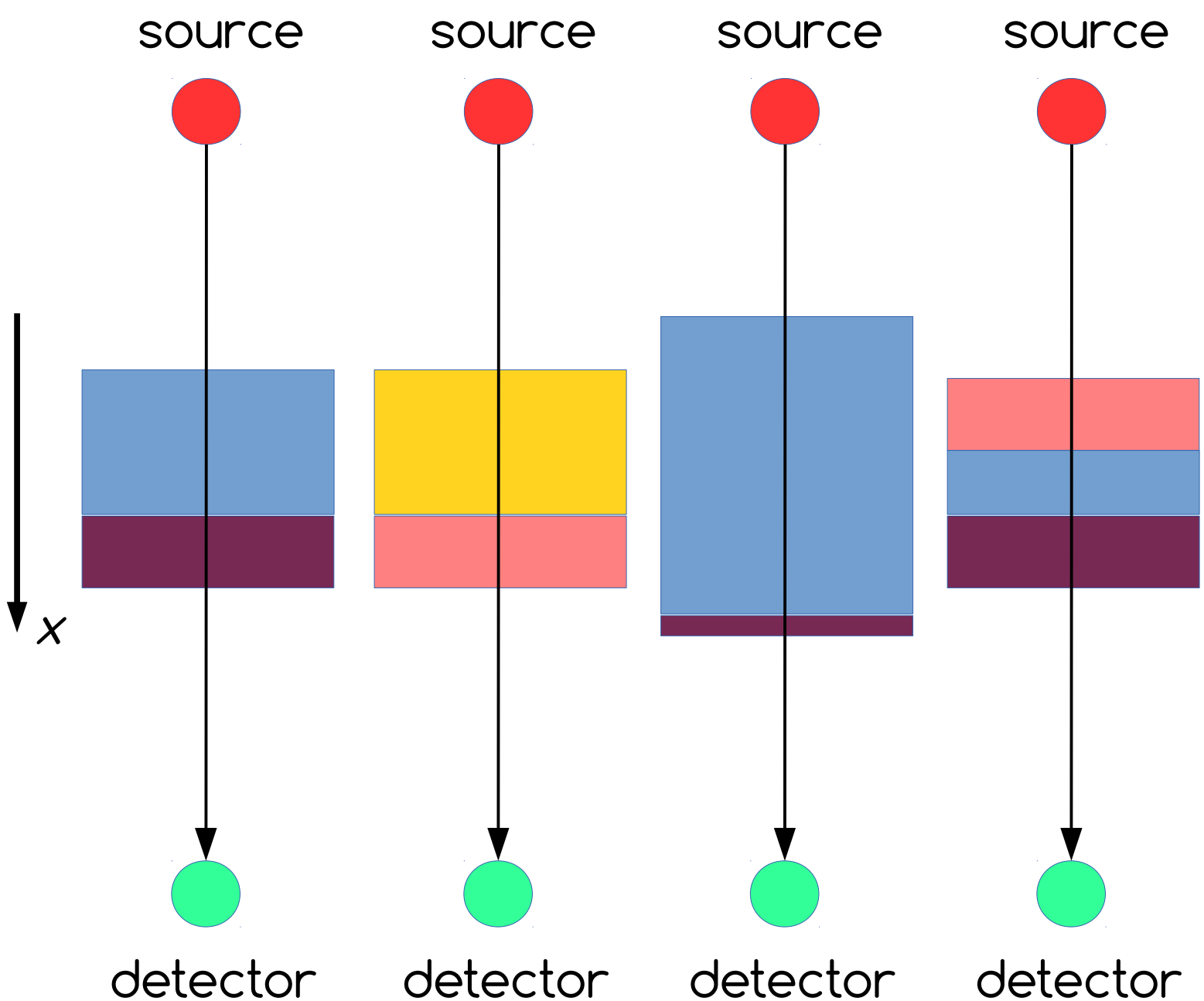

γ
γ
γγγγ

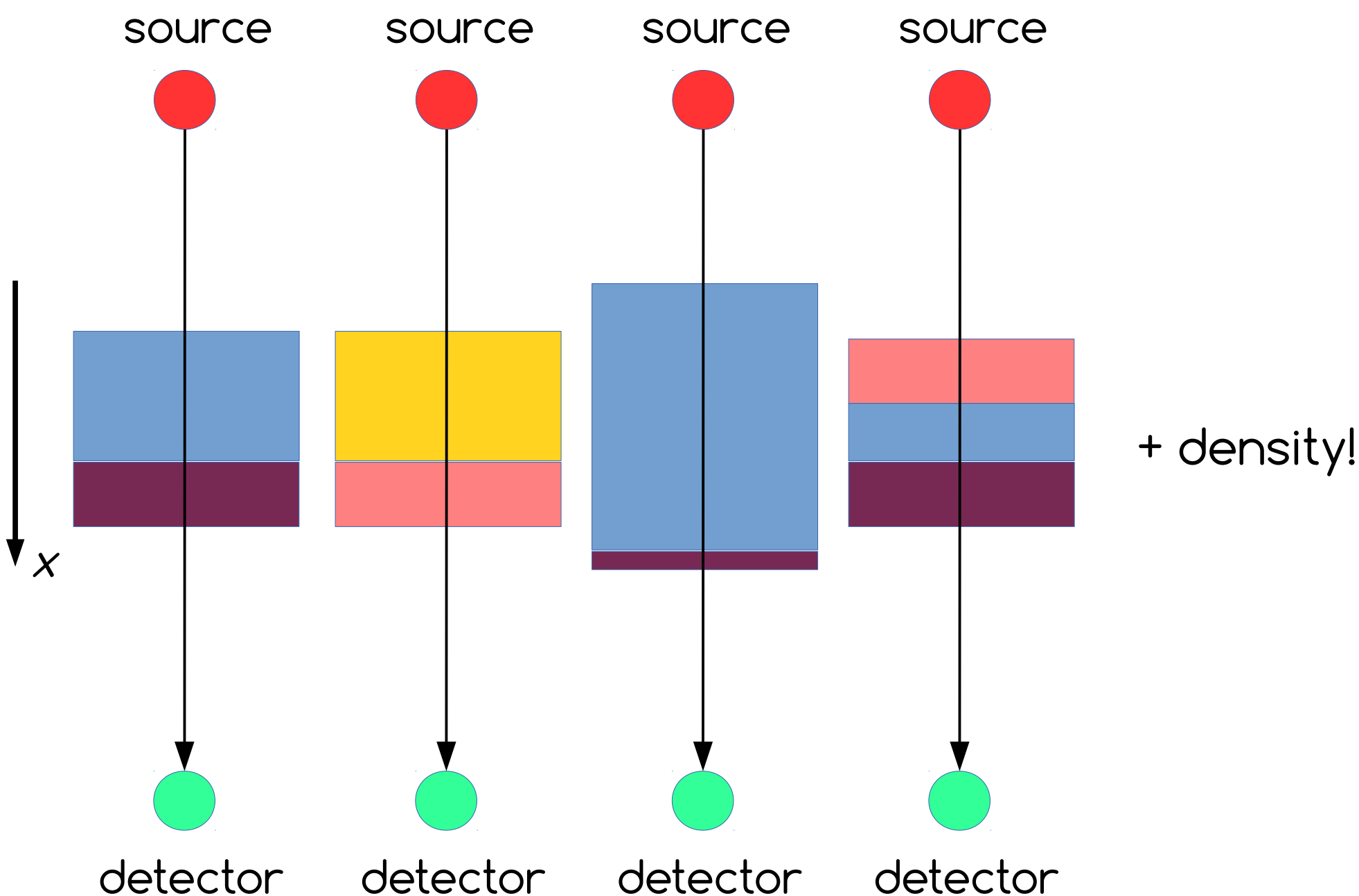
$$N = \boxed{\int_0^{+\infty} dE} N_0(E) e^{-\int_{L_1} \mu_1(x,E)dx - \int_{L_2} \mu_2(x,E)dx}$$

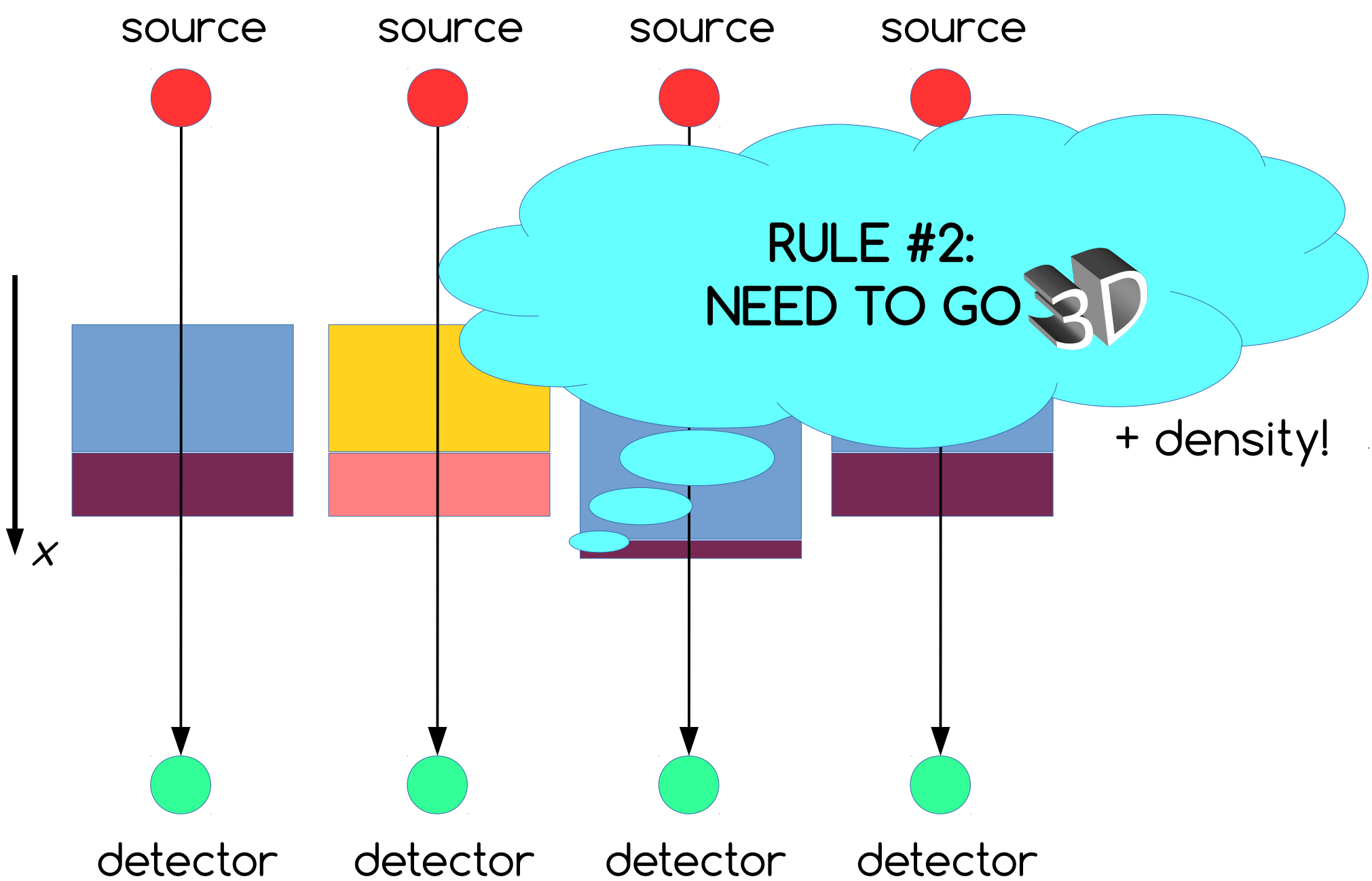

source
x
detector


source
source
x
detector
detector


source
source
source
x
detector
detector
detector

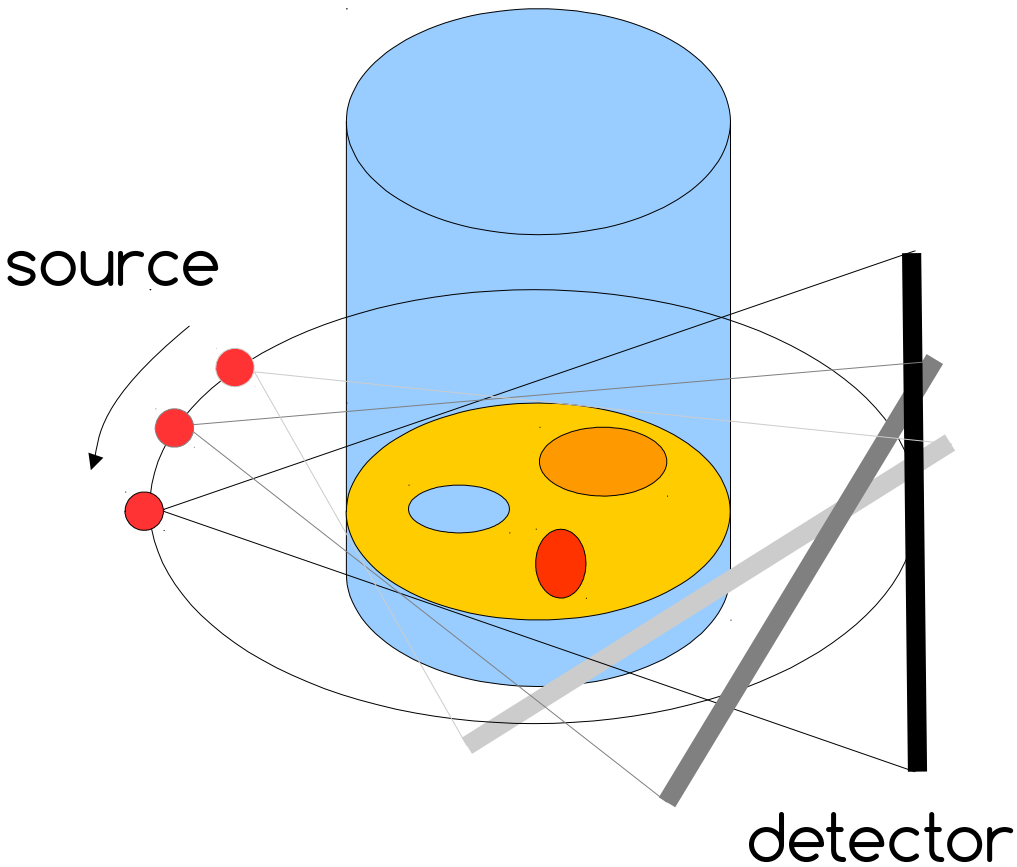

source
source
source
source
x
detector
detector
detector
detector


source
source
source
source
x
+ density!
detector
detector
detector
detector

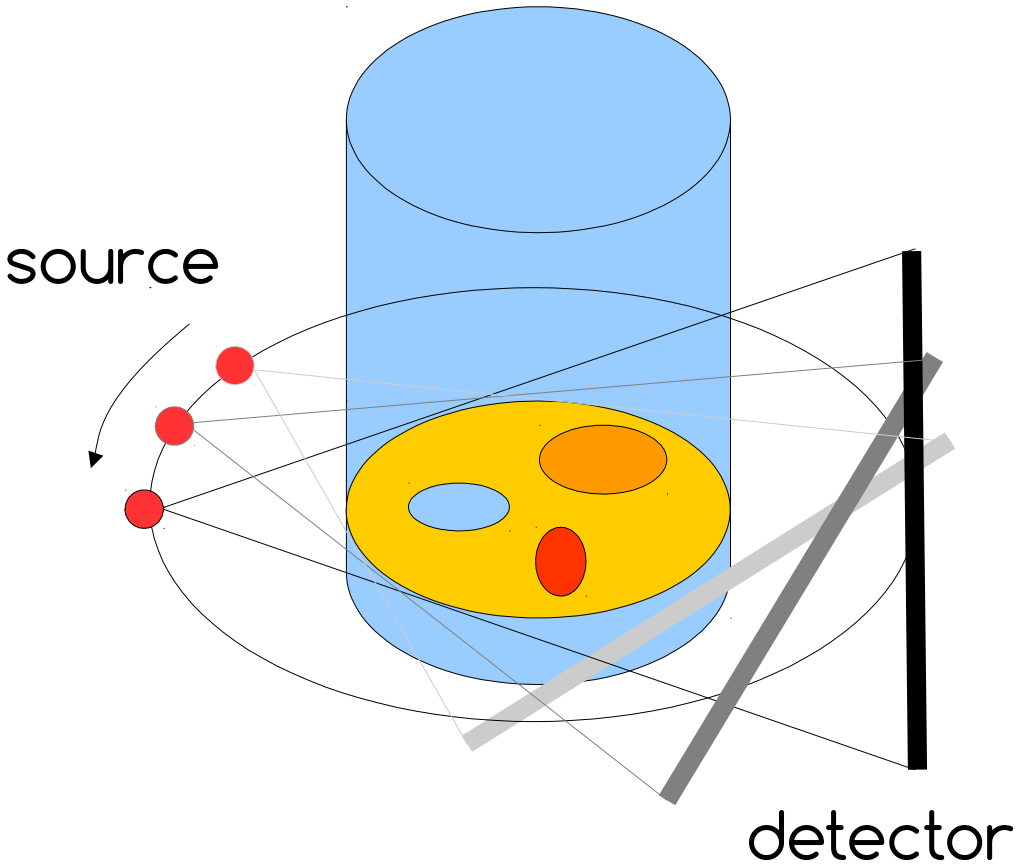

source
source
source
source
RULE #2:
NEED TO GO 3D
+ density!
x
detector
detector
detector
detector

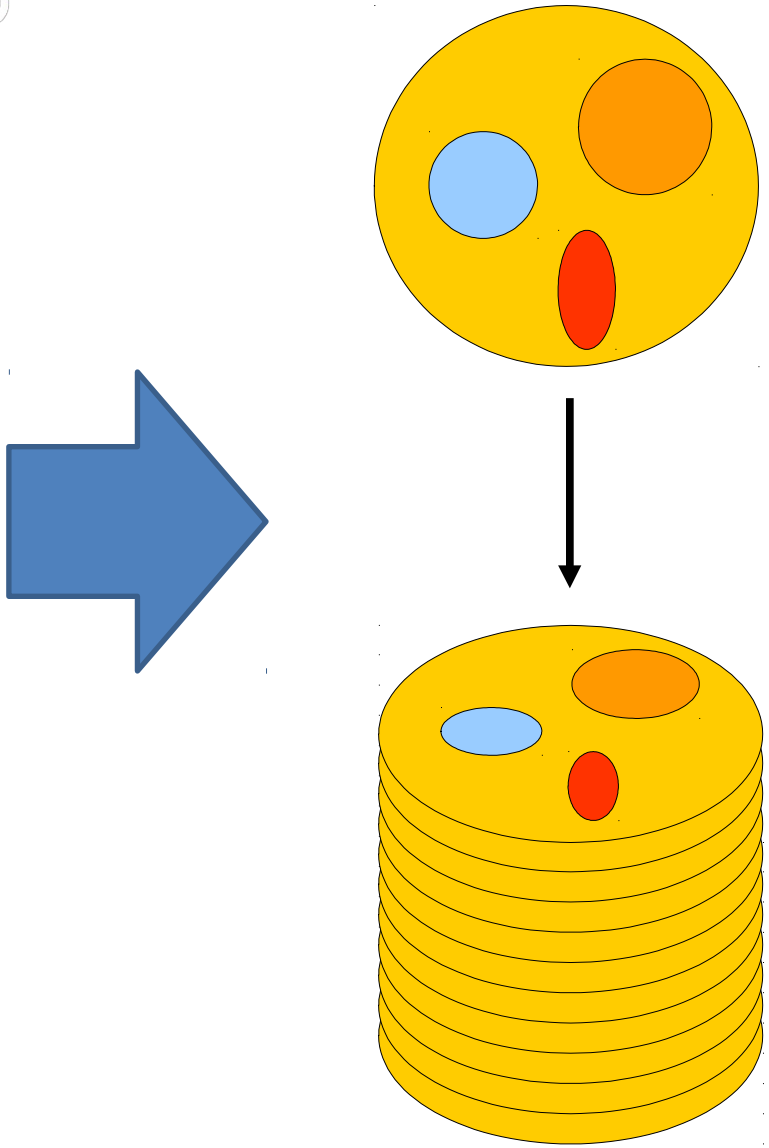
Computed Tomography (CT)

Computed Tomography (CT)



Computed Tomography (CT)





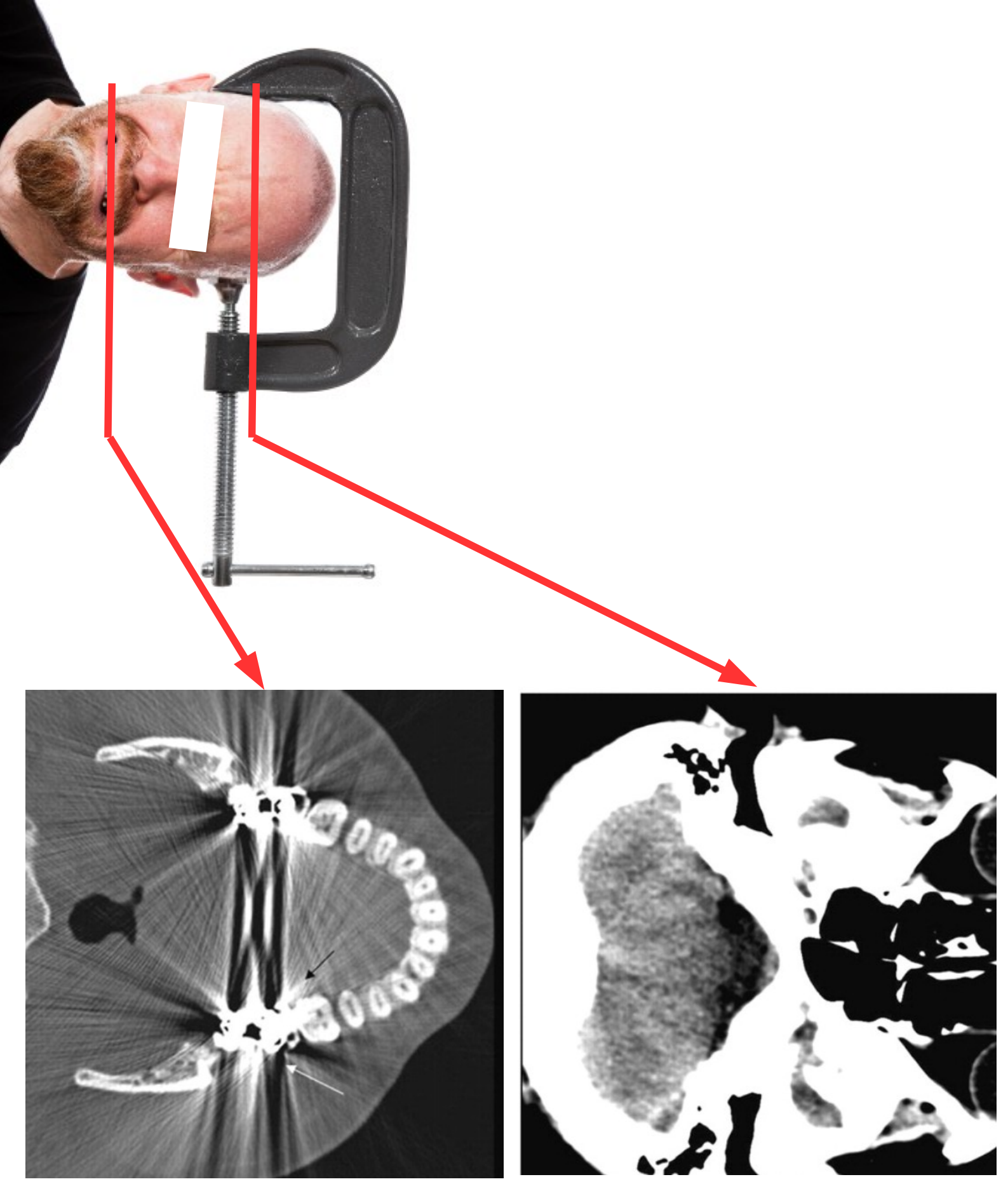


Image credit: R. Popilock, K. Sandrasagaren, L. Harris, and K. A. Kaser. CT Artifact Recognition for the Nuclear Technologist. J. Nucl. Med. Tech., 36(2):79–81, 2008.

Some brain missing?

What the heck is going on here?

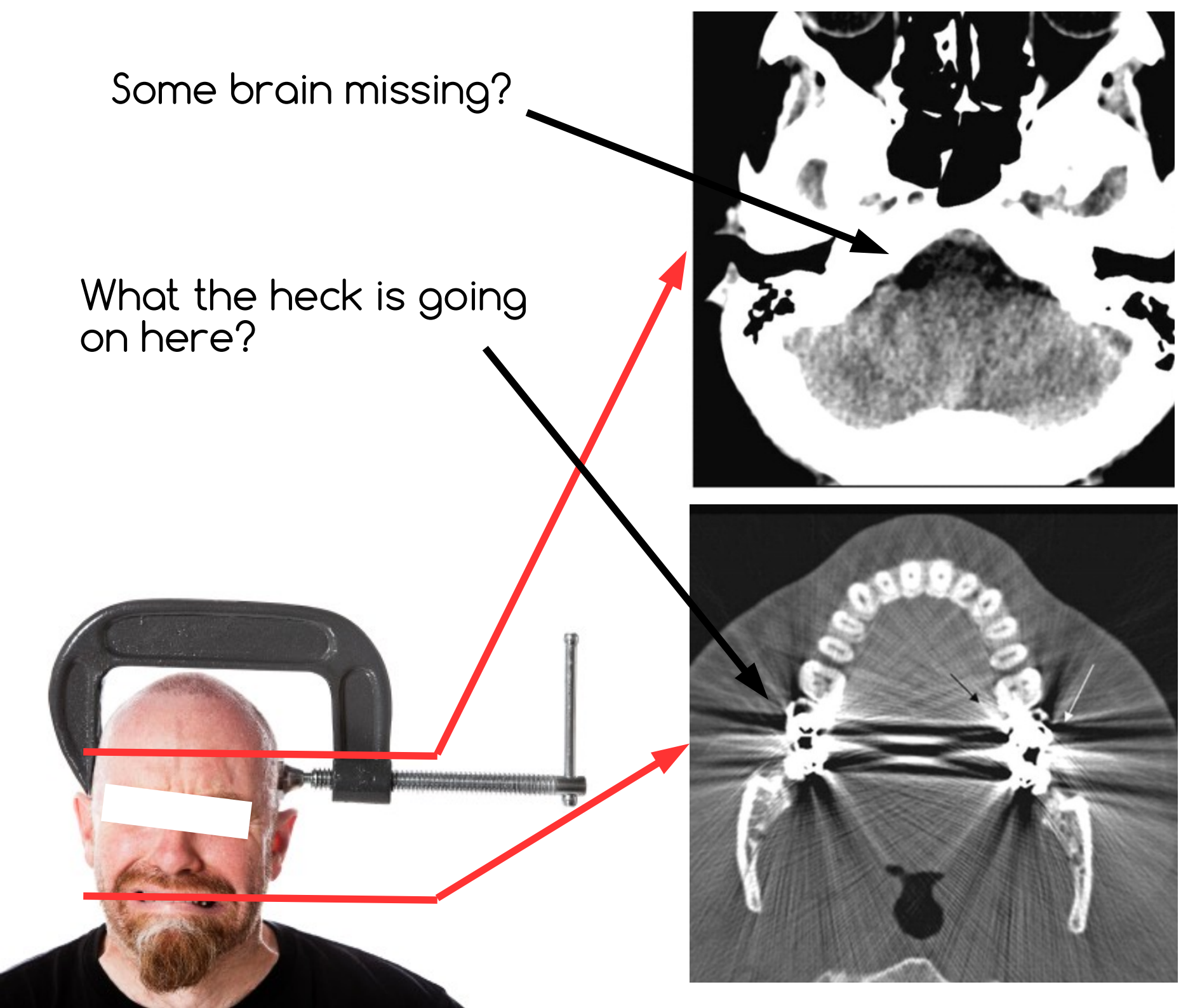
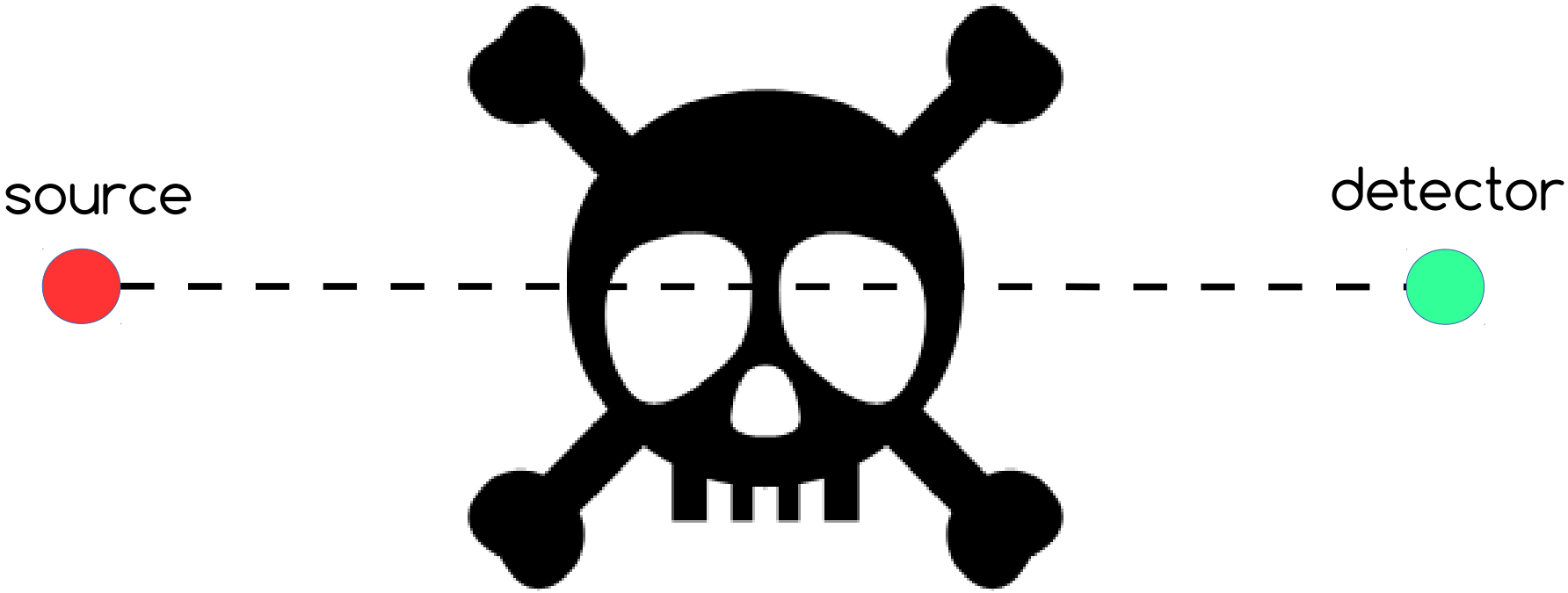
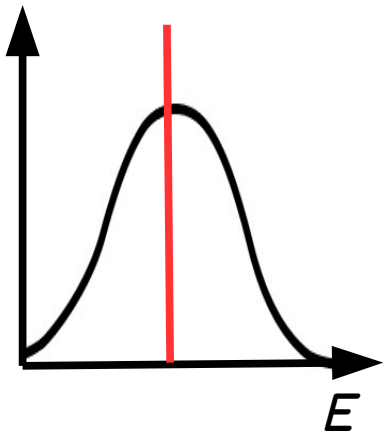


Image credit: R. Popilock, K. Sandrasagaren, L. Harris, and K. A. Kaser. CT Artifact Recognition for the Nuclear Technologist. J. Nucl. Med. Tech., 36(2):79–81, 2008.

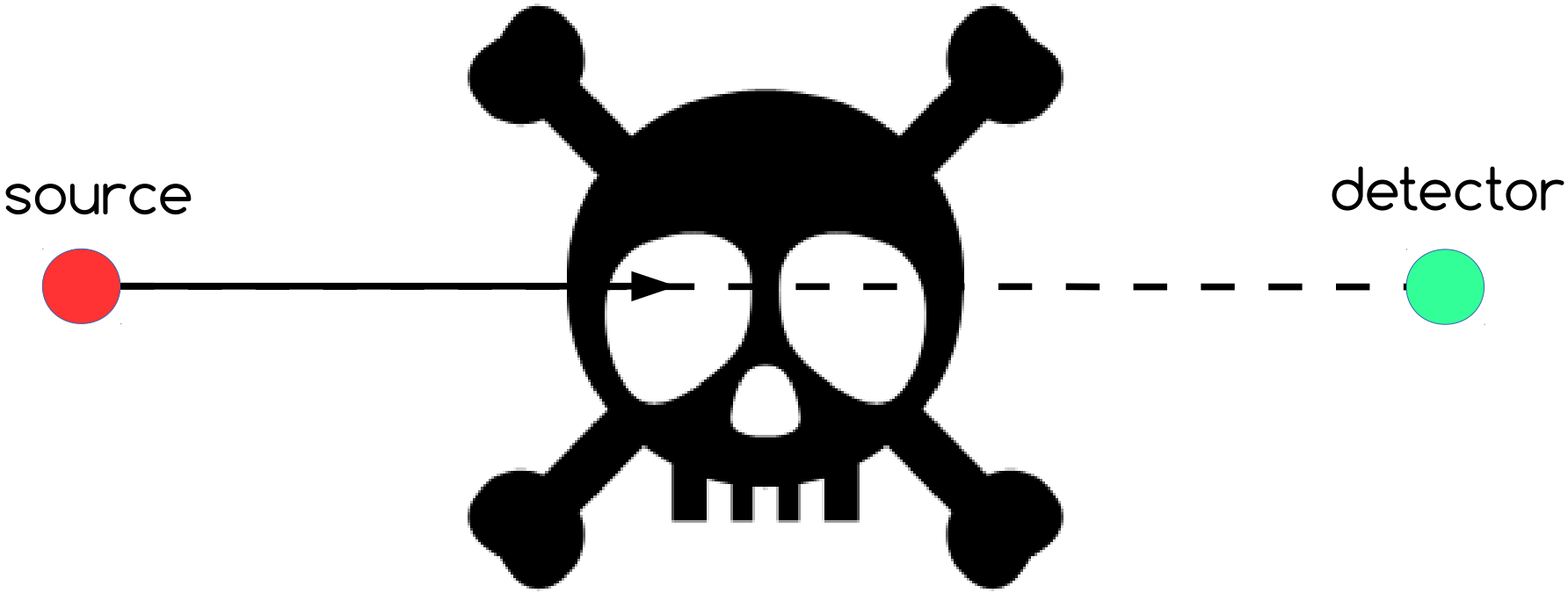
BEAM HARDENING

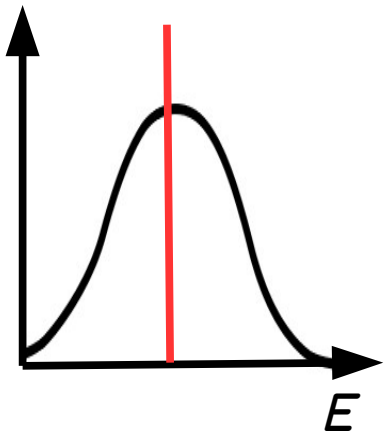
BEAM HARDENING

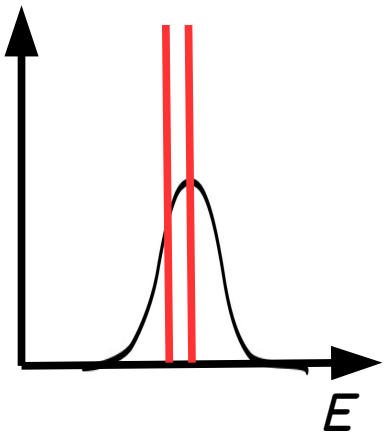




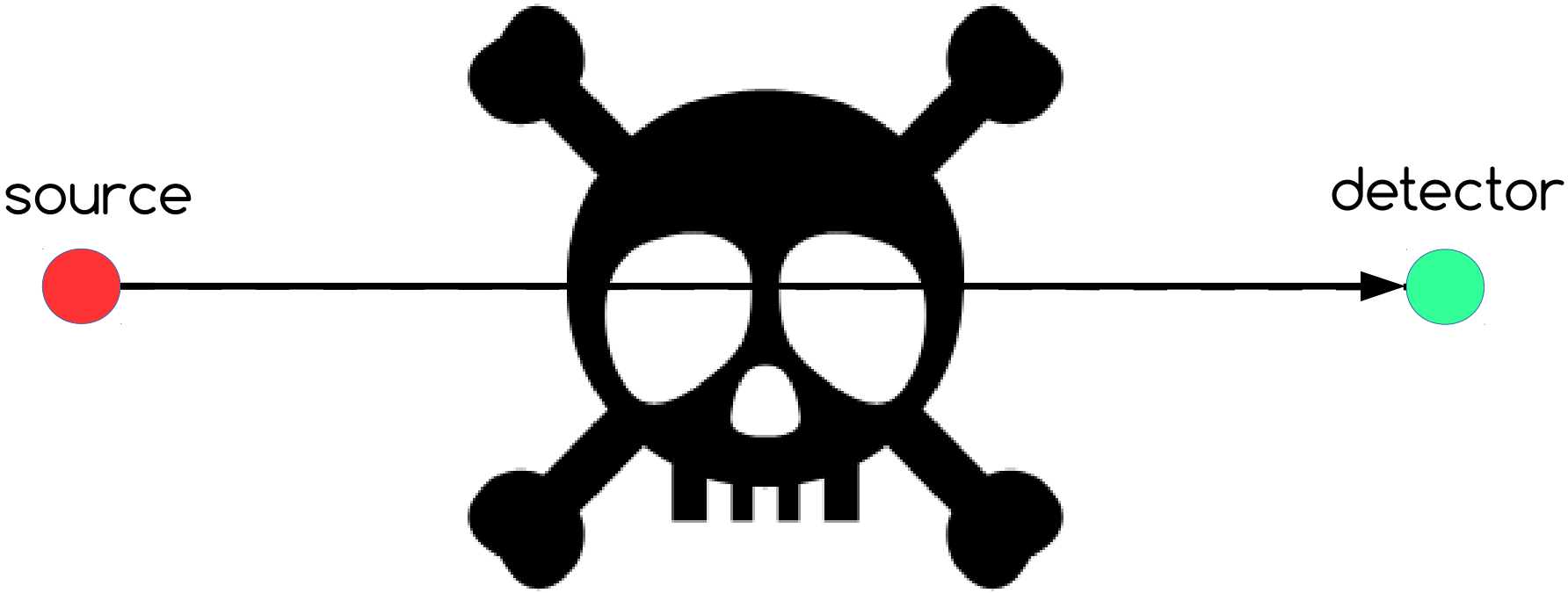
BEAM HARDENING

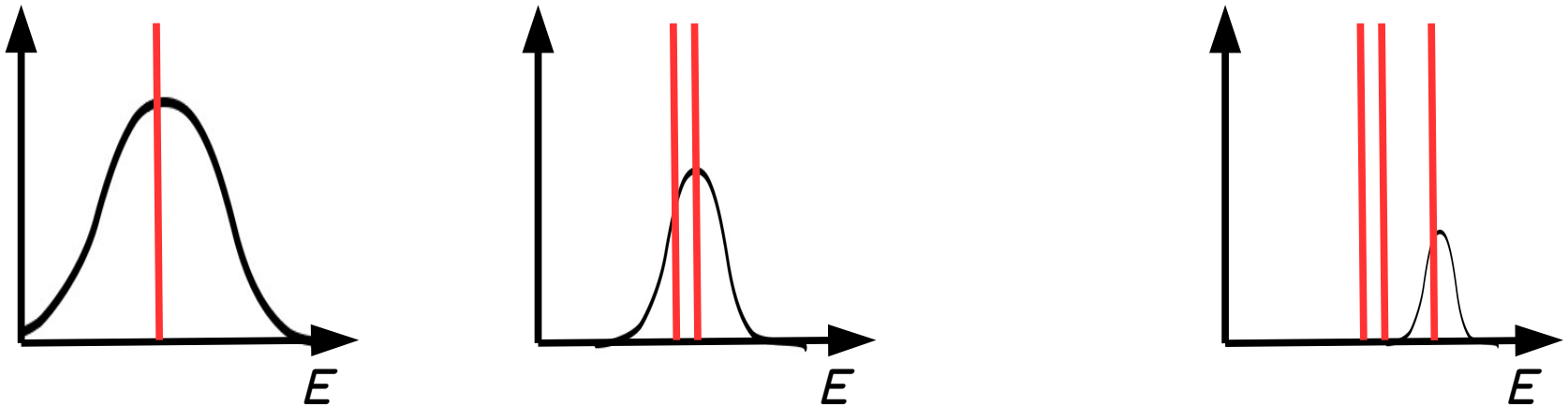




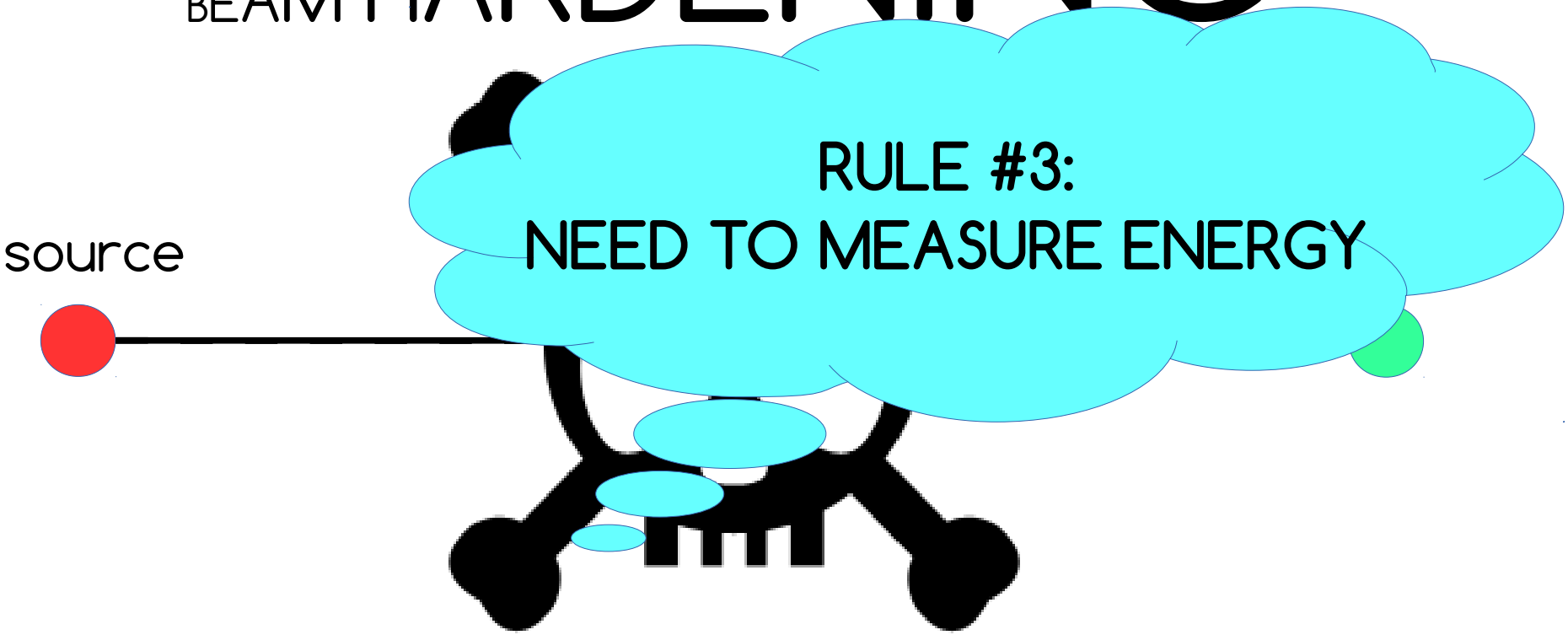


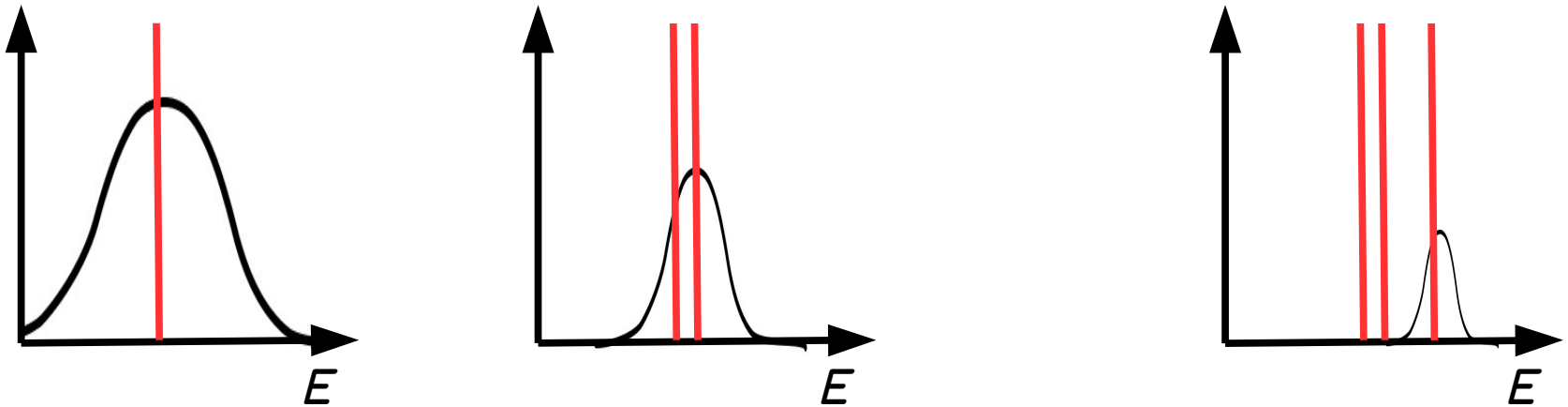
BEAM HARDENING

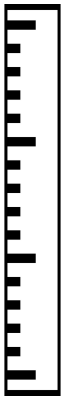


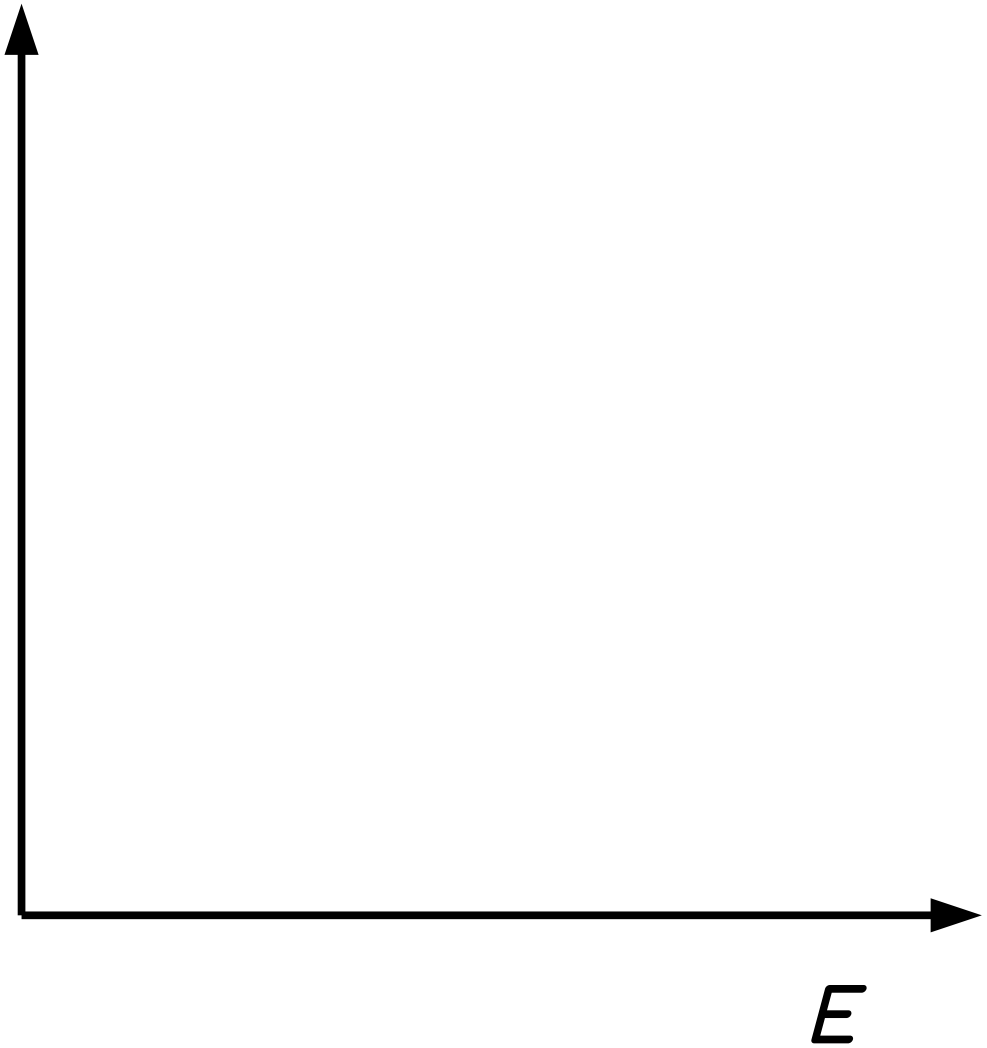


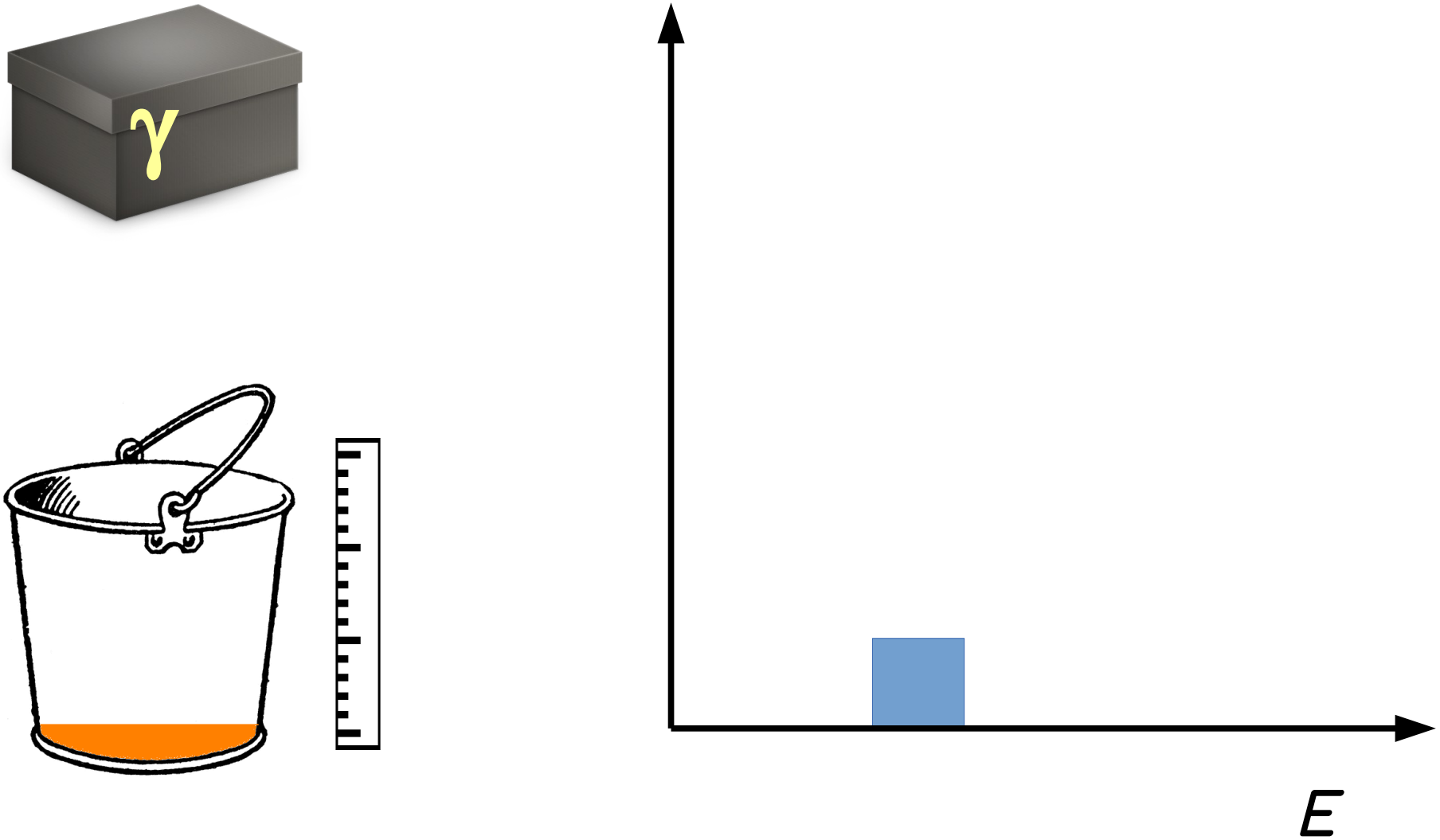
BEAM HARDENING

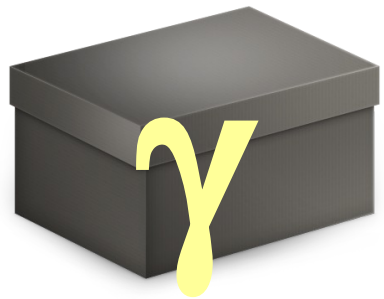


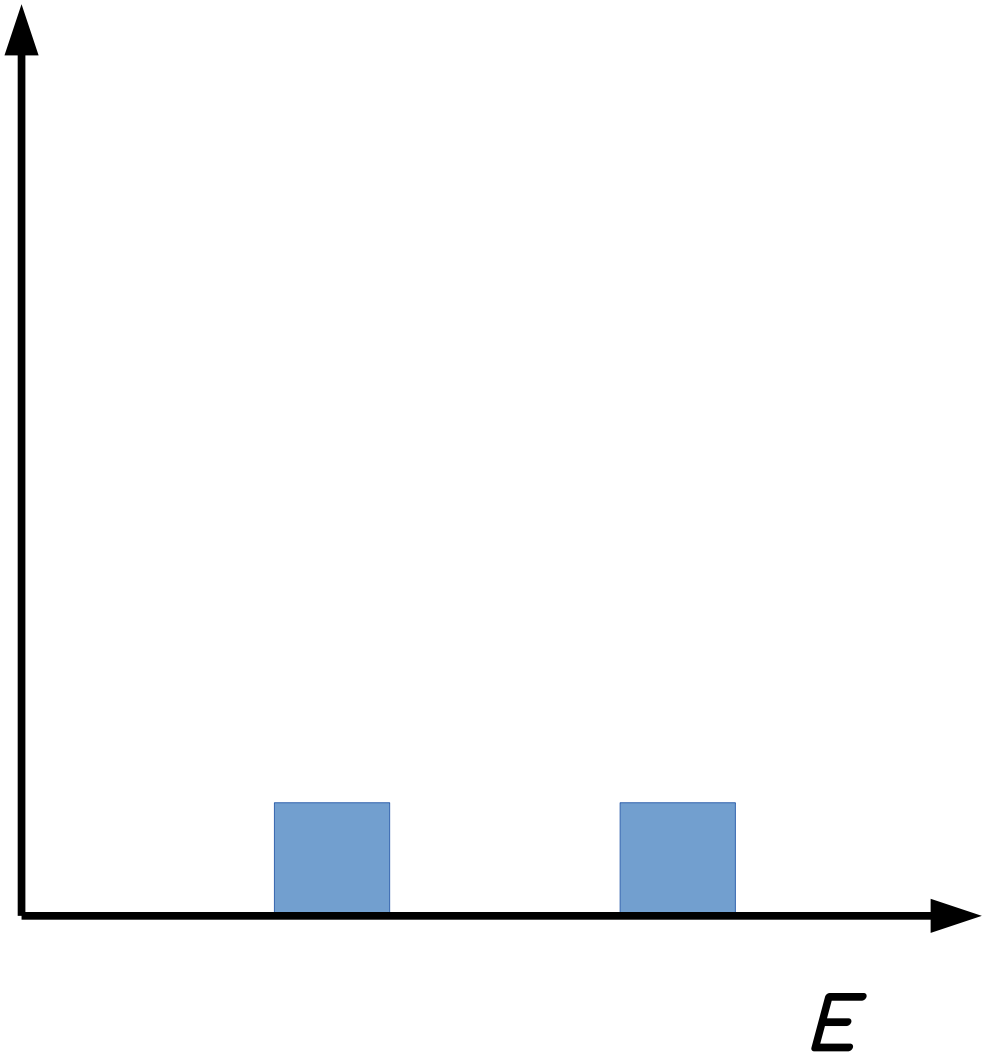


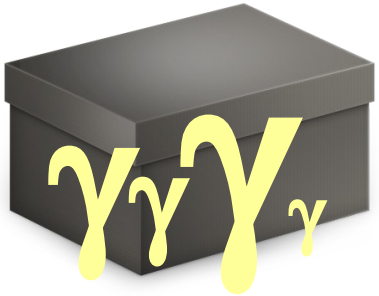


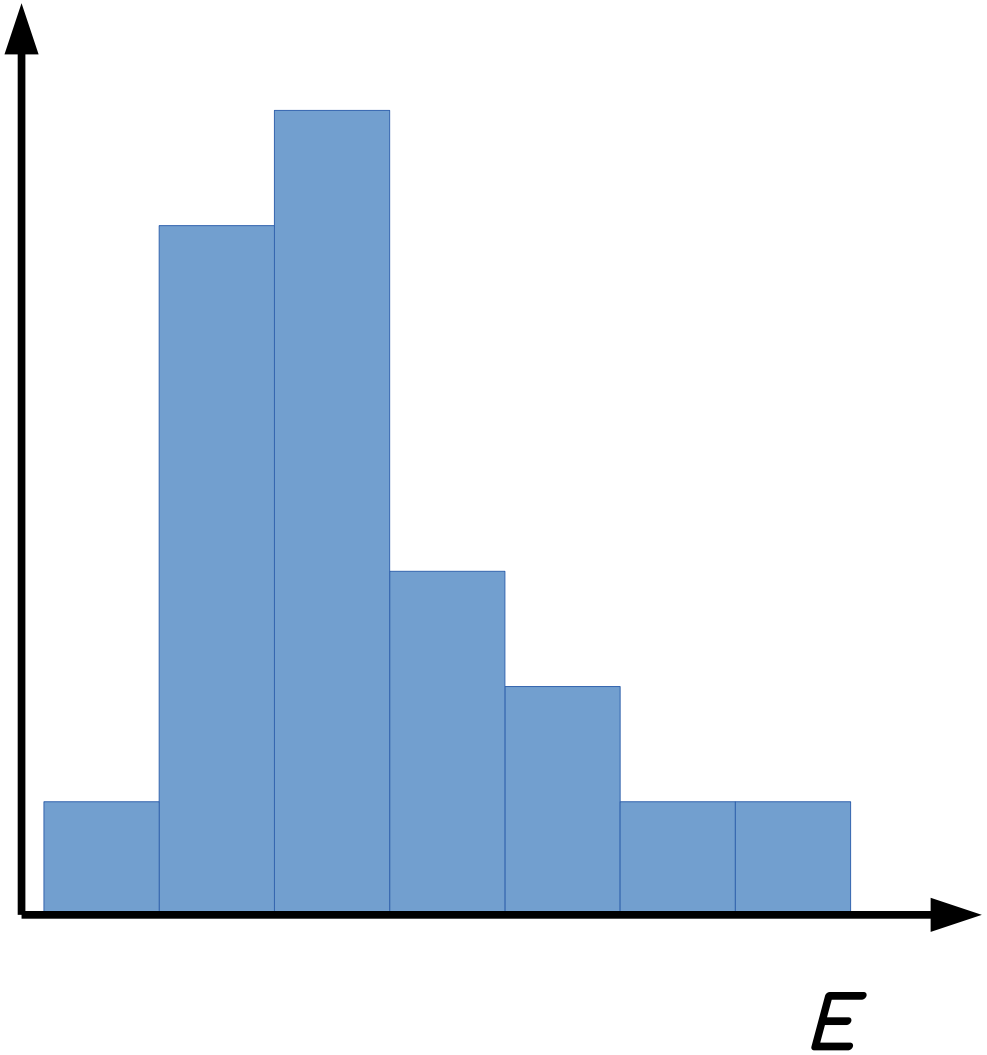

E

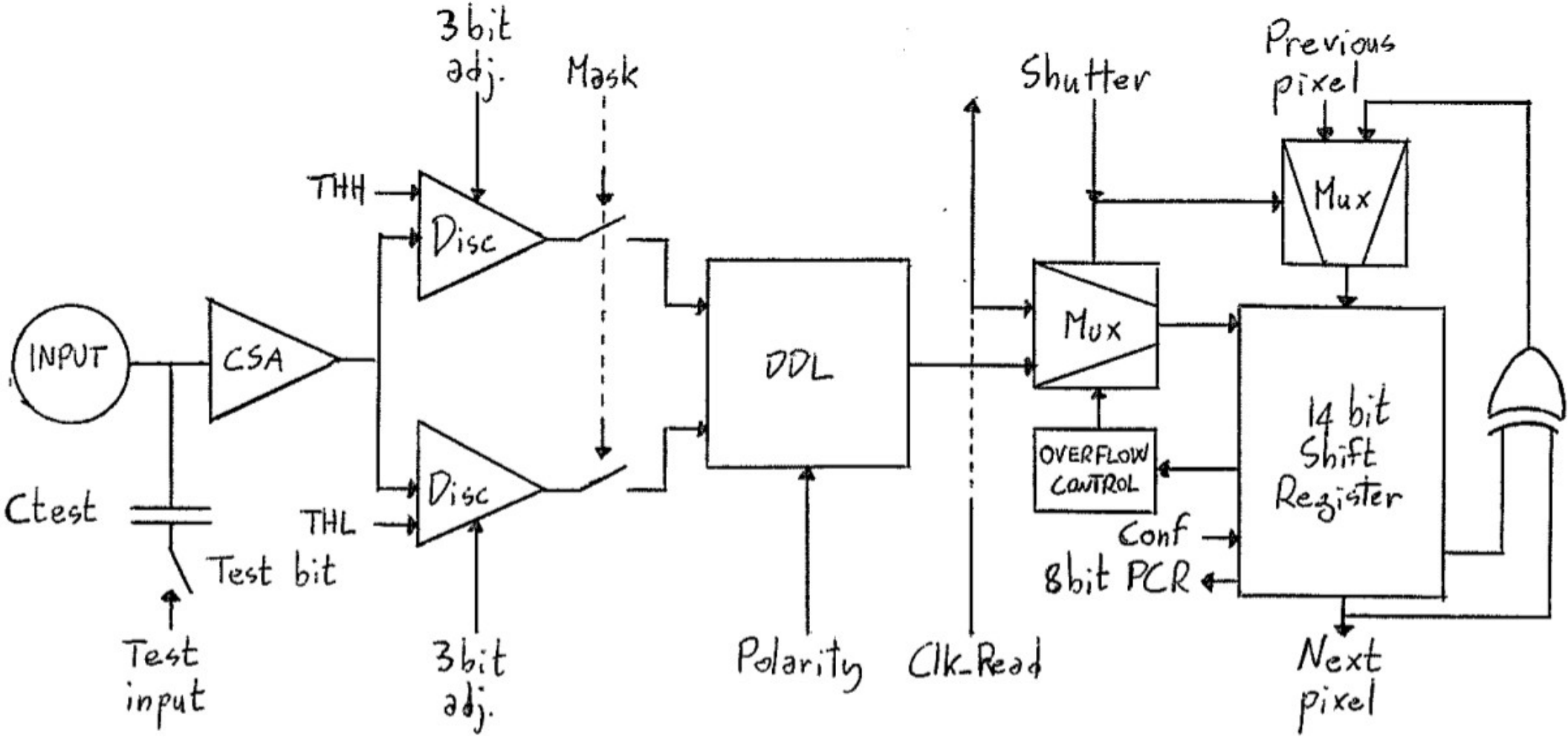

γ
E


γ

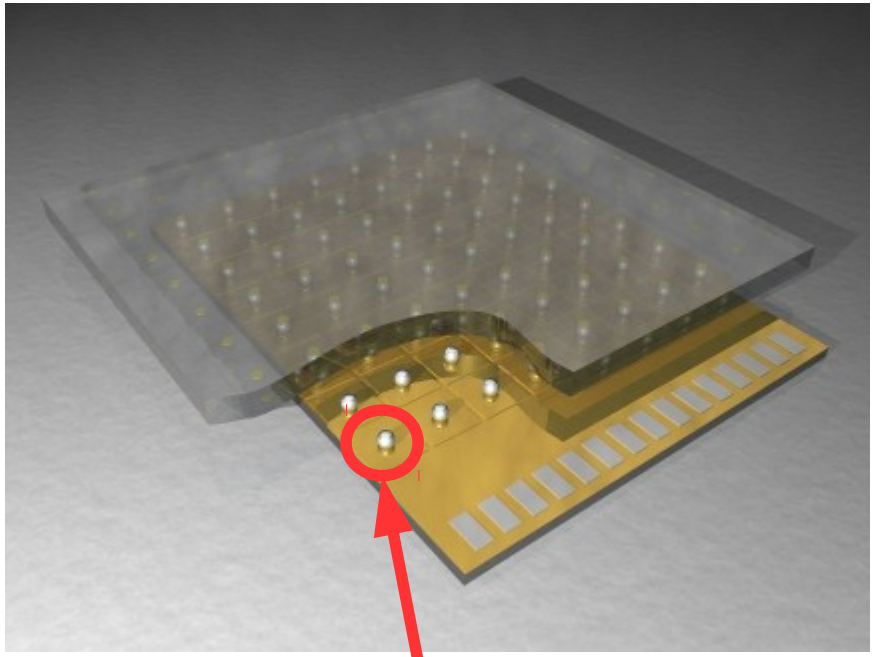

E

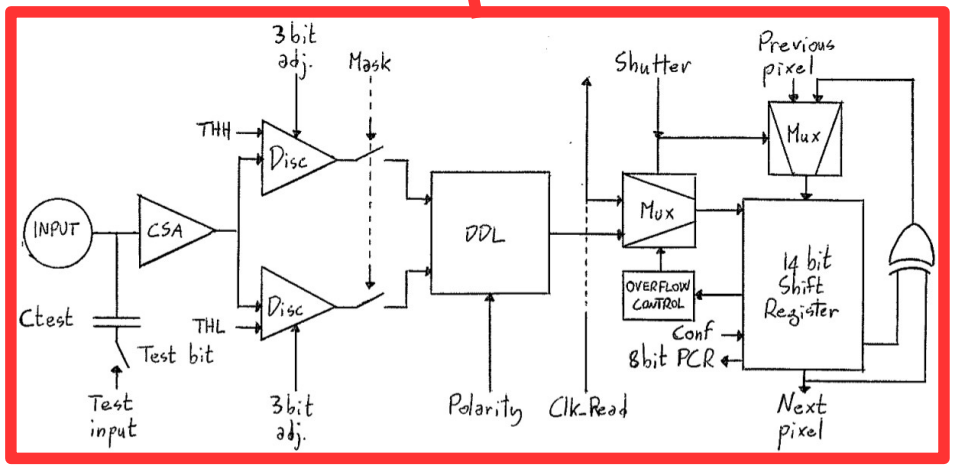

γγγγ

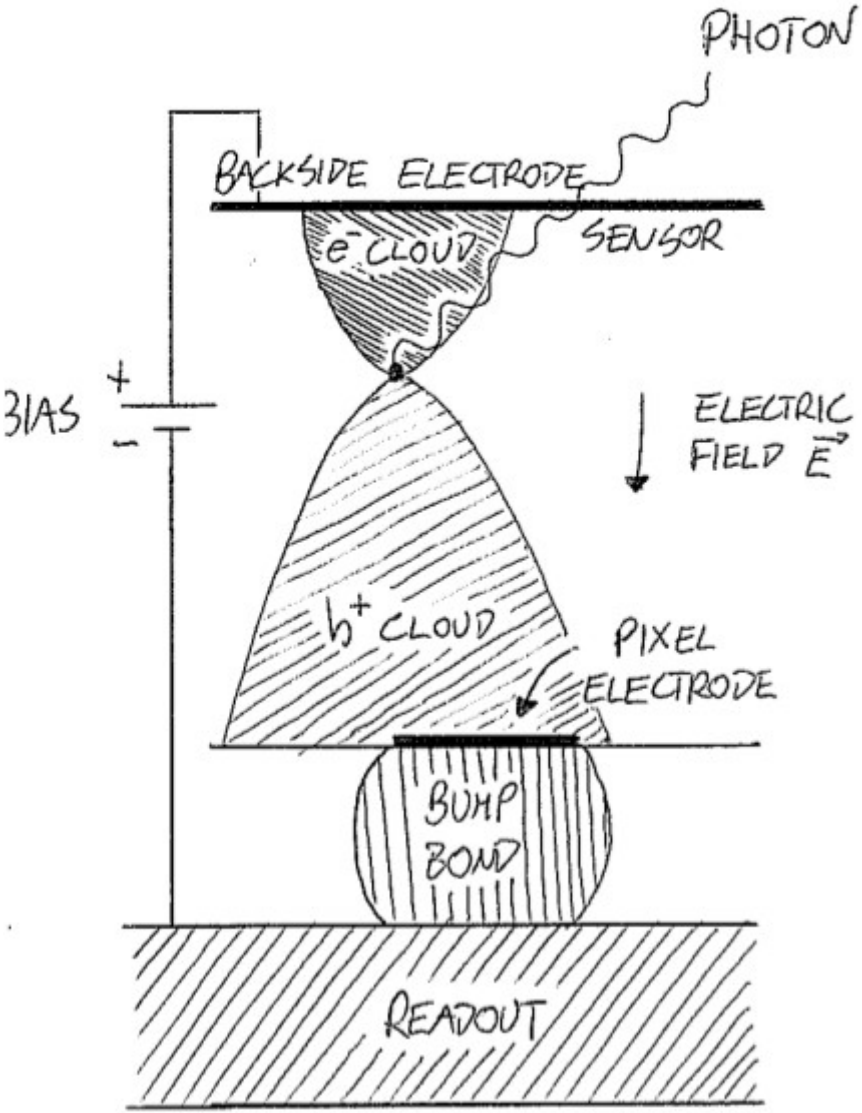

E

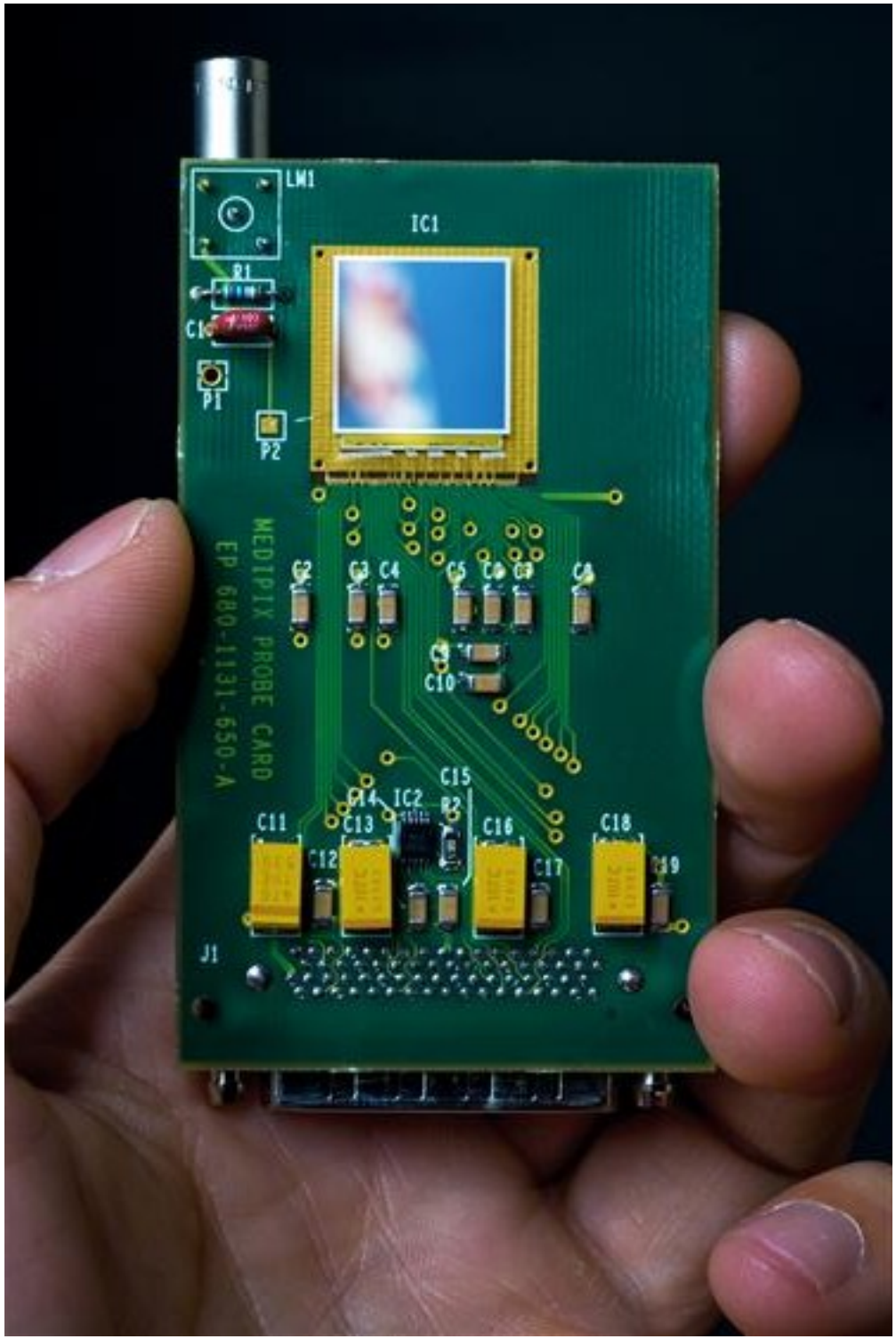

3bit adj.
Mask
Shutter
Previous pixel
THH
Disc
Mux
INPUT
CSA
DDL
Mux
14 bit Shift Register
OVERFLOW CONTROL
Ctest
THL
Disc
Conf
8bit PCR
Test bit
Test input
3bit adj.
Polarity
Clk_Read
Next pixel

Hybrid pixel detectors









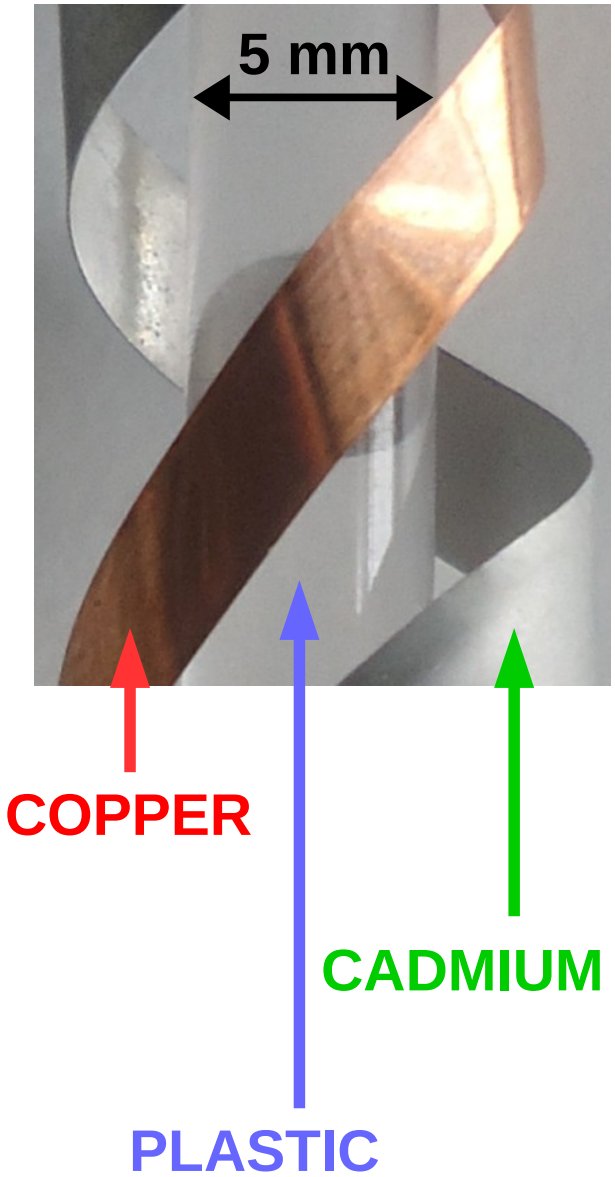
Medipix

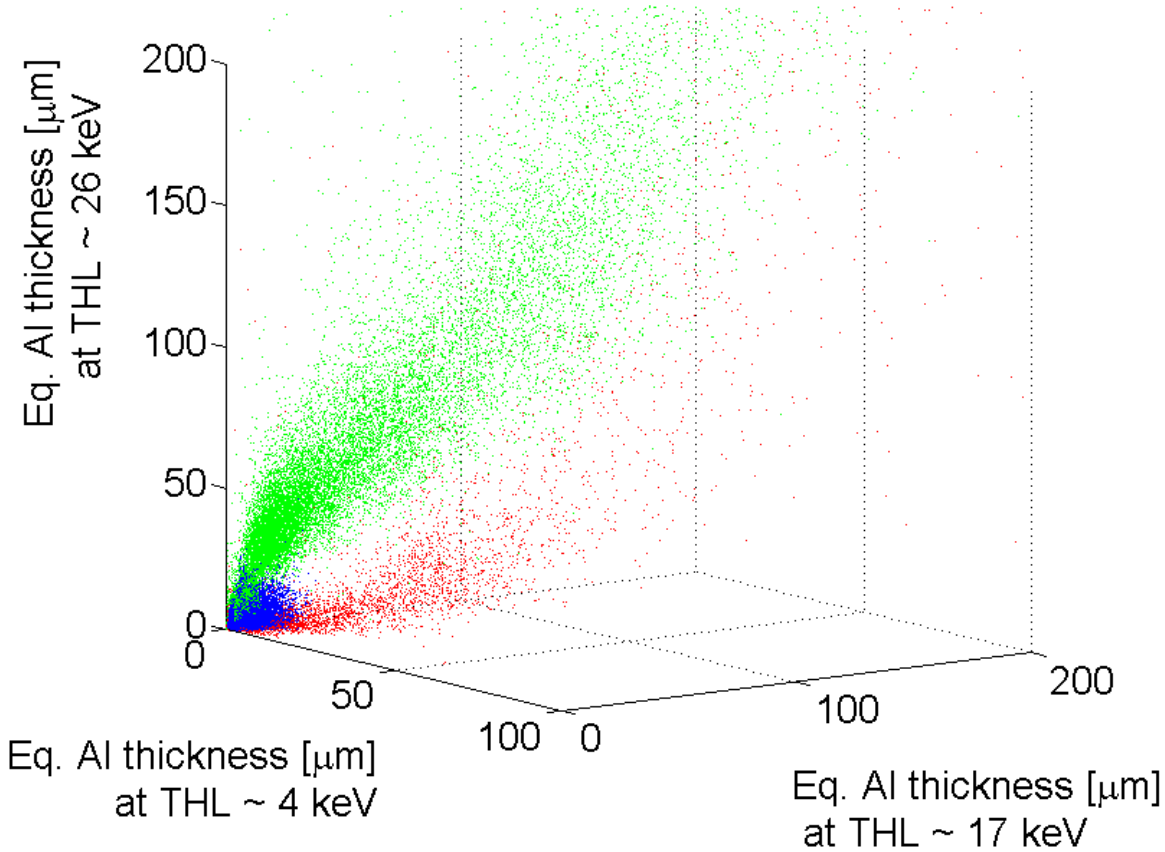
- 256 x 256 = 64k (active) pixels
- Pixel pitch = 55 um
- Electronic noise free
- High dynamic range (depth of the photon counter)
- 3-side tilable → larger area
- Up to 8 simultaneous thresholds

Medipix

- 256 x 256 = 64k (active) pixels
- ge (depth of
  unter)
- 3-side tilable → larger area
- Up to 8 simultaneous thresholds

RULE #4:
#materials = #thresholds


5 mm
COPPER
CADMIUM
PLASTIC


Eq. Al thickness [μm]
at THL ~ 26 keV
200
150
100
50
0
0
50
100
Eq. Al thickness [μm]
at THL ~ 4 keV
0
100
200
Eq. Al thickness [μm]
at THL ~ 17 keV

Conventional = monochromatic approximation

Conventional = monochromatic approximation

$$N = N_0 e^{-\int_L \mu(x)\,dx}$$

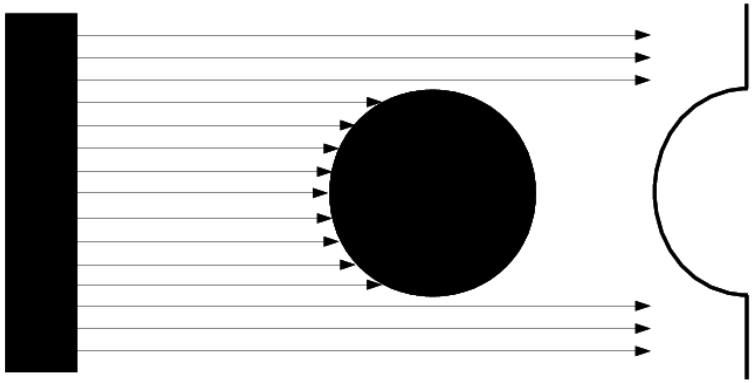
Conventional = monochromatic approximation

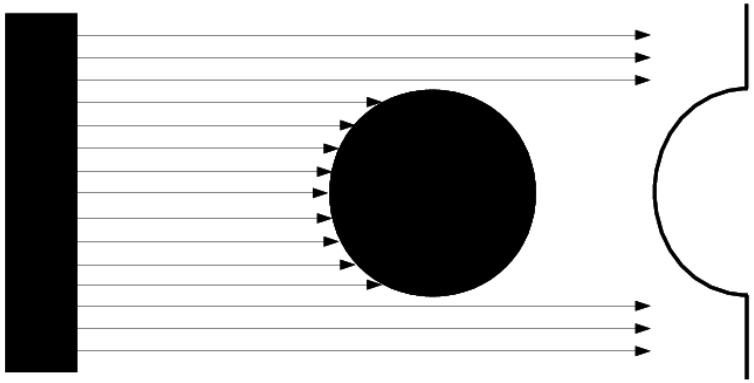
$$N = N_0 e^{-\int_L \mu(x)dx} \Rightarrow -\int_L \mu(x)dx = \log\frac{N}{N_0}$$

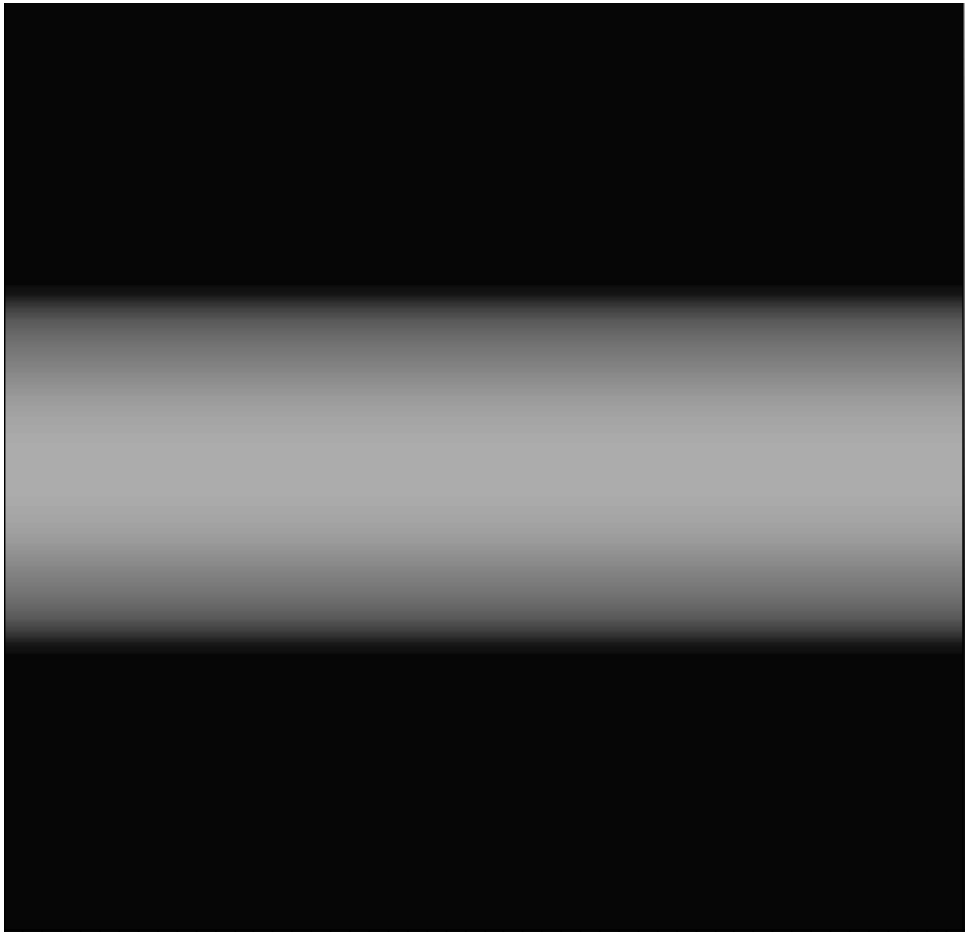
Conventional = monochromatic approximation

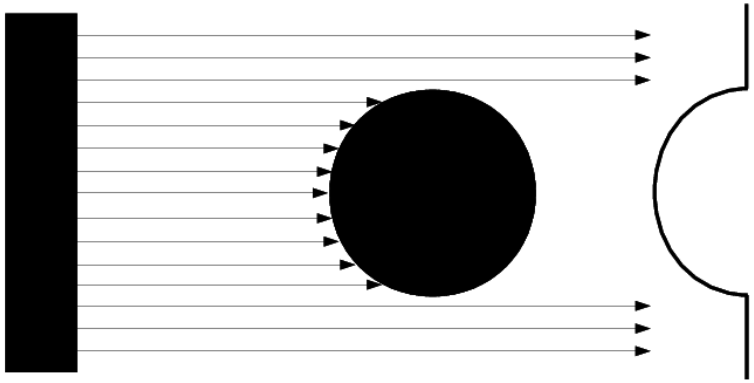
$$N = N_0 e^{-\int_L \mu(x)dx} \Rightarrow -\int_L \mu(x)dx = \log\frac{N}{N_0}$$

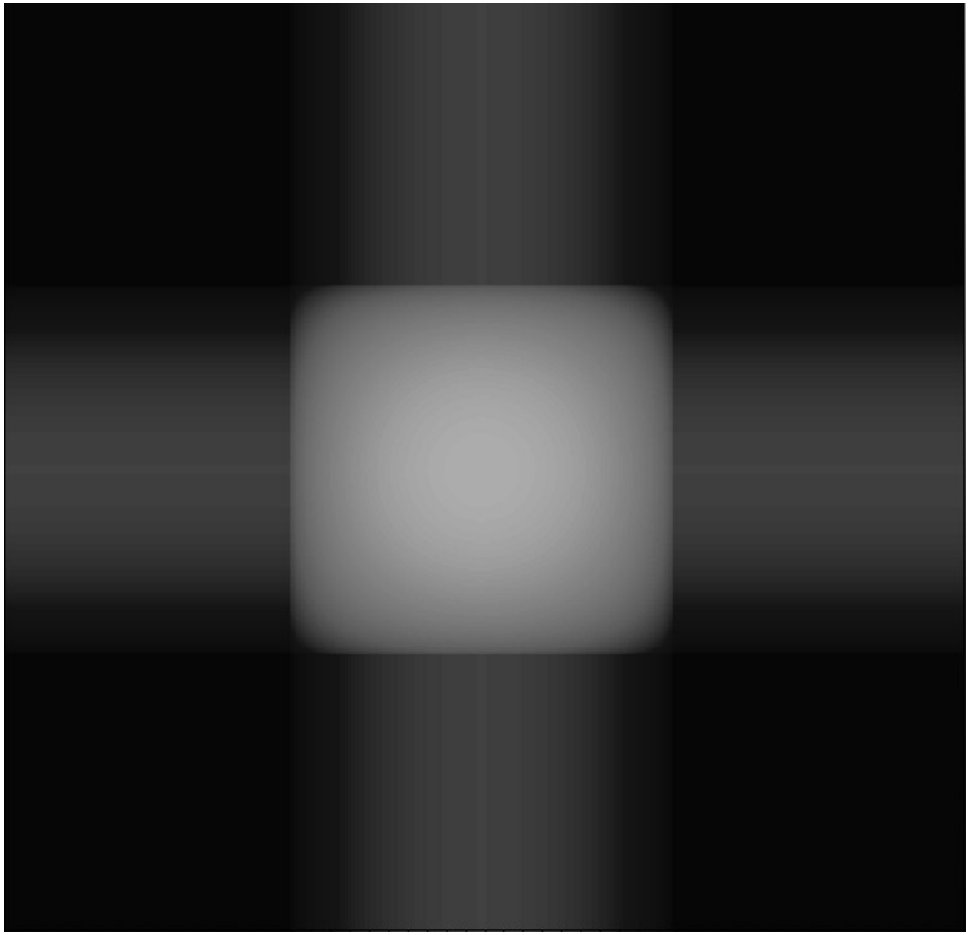
$$N = \int_0^{+\infty} dE\, N_0(E) e^{-\int_L \mu(x,E)dx} \Rightarrow$$

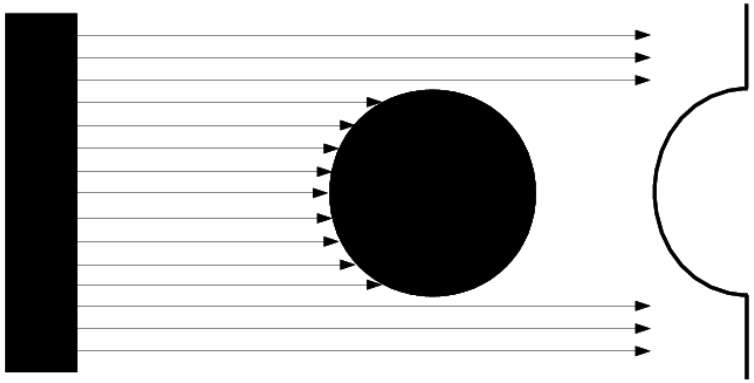


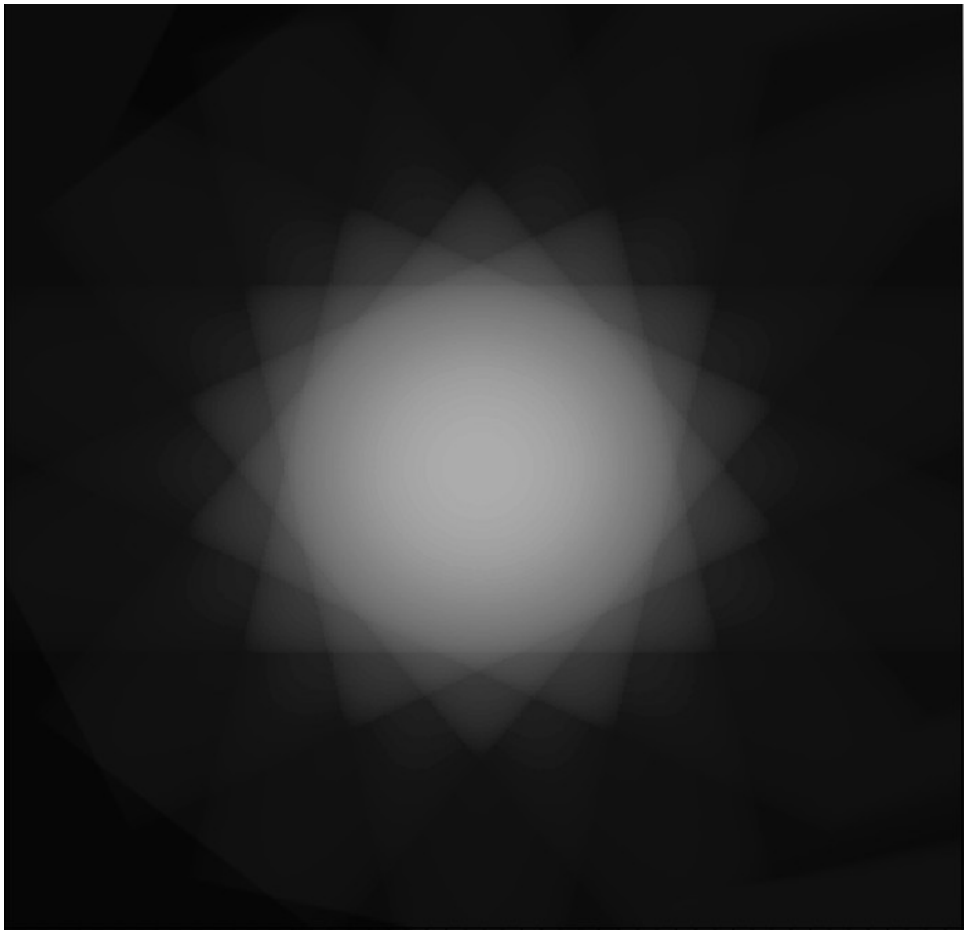












$$N_{l\theta}^{thr} = \int_{0}^{+\infty} d$$

WHATEVER
COMPLICATED
INTEGRAND

$$N_{l\theta}^{thr} = \int_{0}^{+\infty} d$$

WHATEVER COMPLICATED INTEGRAND

This number obeys Poisson statistics

$$P\left(X_{l\theta}^{thr} \middle| N_{l\theta}^{thr}\right) = \frac{N_{l\theta}^{thr\,X_{l\theta}^{thr}}\, e^{-N_{l\theta}^{thr}}}{X_{l\theta}^{thr}\,!}$$

$$N_{l\theta}^{thr} = \int_{0}^{+\infty} d$$

WHATEVER COMPLICATED INTEGRAND

This number obeys Poisson statistics

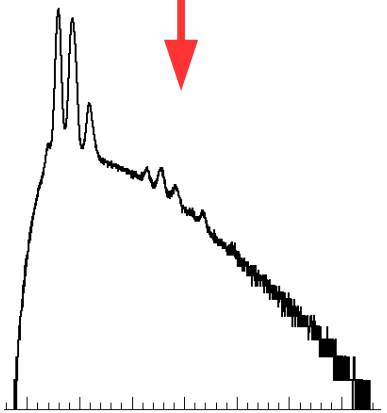
$$P\left(X_{l\theta}^{thr} | N_{l\theta}^{thr}\right) = \frac{N_{l\theta}^{thr\, X_{l\theta}^{thr}} e^{-N_{l\theta}^{thr}}}{X_{l\theta}^{thr}!}$$

Independent variables approximation

$$P\left(X | N\right) = \prod_{l\theta\, thr} \frac{N_{l\theta}^{thr\, X_{l\theta}^{thr}} e^{-N_{l\theta}^{thr}}}{X_{l\theta}^{thr}!}$$

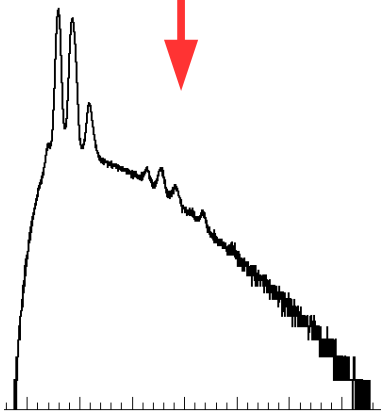
$$N_{l\theta}^{thr} = \int_{E_l^{thr}}^{\infty} dE \int_0^{\infty} dE' R\left(E; E'\right) S_0\left(E\right) e^{-\sum_n \rho_n \frac{\mu_n}{\rho_n}(E) \int_{l\theta} f_n(x) dx}$$

$$N_{l\theta}^{thr} = \int_{E_l^{thr}}^{\infty} dE \int_0^{\infty} dE' R(E;E') \boxed{S_0(E)} e^{-\sum_n \rho_n \frac{\mu_n}{\rho_n}(E) \int_{l\theta} f_n(x)\,dx}$$



(measured)
source
spectrum

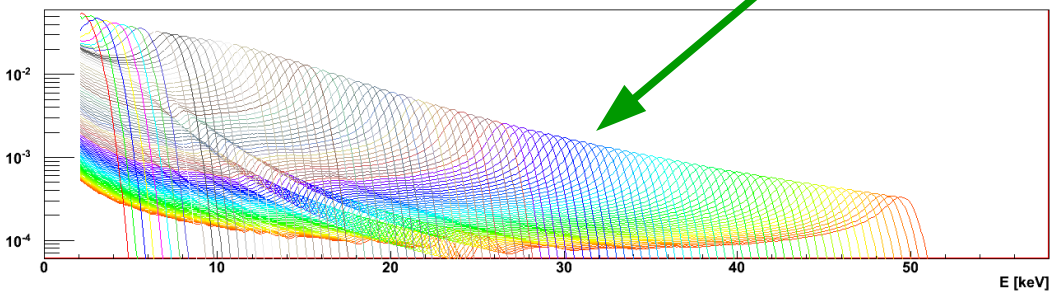
$$N_{l\theta}^{thr} = \int_{E_l^{thr}}^{\infty} dE \int_0^{\infty} dE' R(E;E') \boxed{S_0(E)} e^{-\sum_n \boxed{\rho_n \frac{\mu_n}{\rho_n}(E)} \int_{l\theta} f_n(x)\,dx}$$



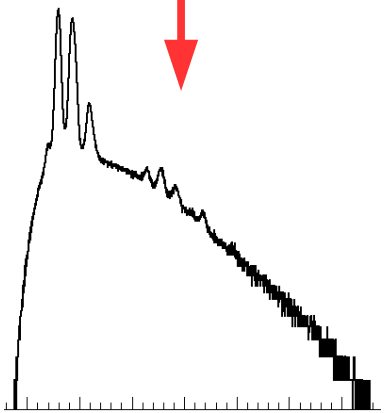
(measured) source spectrum

(known) absorption coefficients + (nominal) densities

$$N_{l\theta}^{thr} = \int_{E_l^{thr}}^{\infty} dE \int_0^{\infty} dE' \boxed{R(E;E')} \boxed{S_0(E)} e^{-\sum_n \boxed{\rho_n \frac{\mu_n}{\rho_n}(E)} \int_{l\theta} f_n(x)\,dx}$$



(measured)
Detector response function



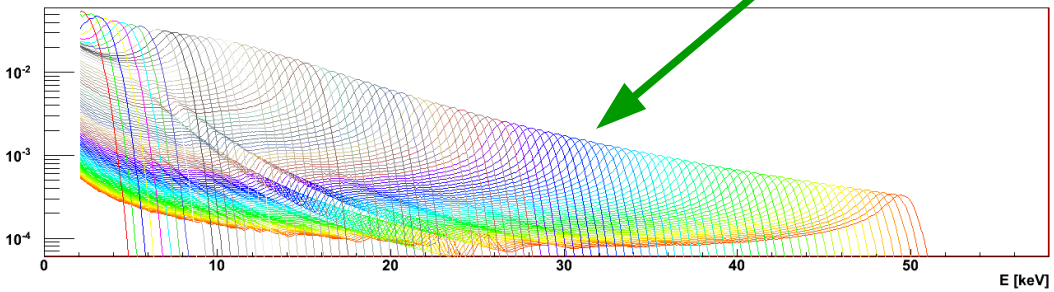
(measured)
source
spectrum

(known)
absorption
coefficients
+
(nominal)
densities

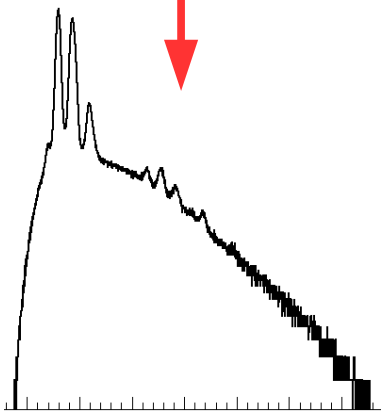
$$N_{l\theta}^{thr} = \int_{E_l^{thr}}^{\infty} dE \int_0^{\infty} dE' \, R(E;E') \, S_0(E) \, e^{-\sum_n \rho_n \frac{\mu_n}{\rho_n}(E) \int_{l\theta} f_n(x)\,dx}$$

(unknown)
Vector image

(known)
absorption
coefficients
+
(nominal)
densities



(measured)
Detector response function

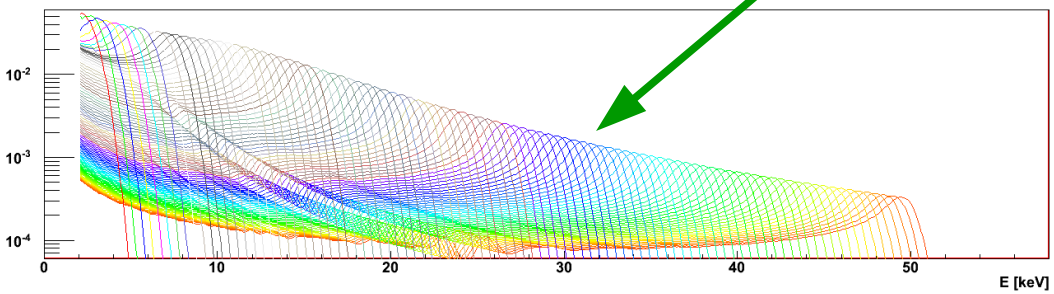


(measured)
source
spectrum

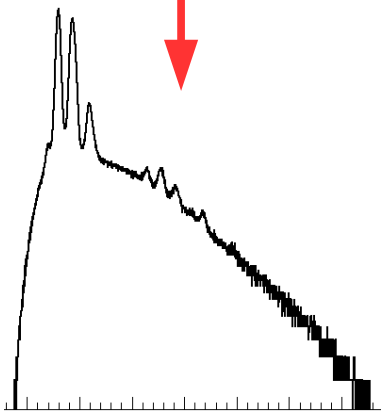
$$N_{l\theta}^{thr} = \int_{E_l^{thr}}^{\infty} dE \int_0^{\infty} dE' \, R(E;E') \, S_0(E) \, e^{-\sum_n \rho_n \frac{\mu_n}{\rho_n}(E) \int_{l\theta} f_n(x)\,dx}$$

(unknown)
Vector image

(known)
absorption
coefficients
+
(nominal)
densities



(measured)
Detector response function



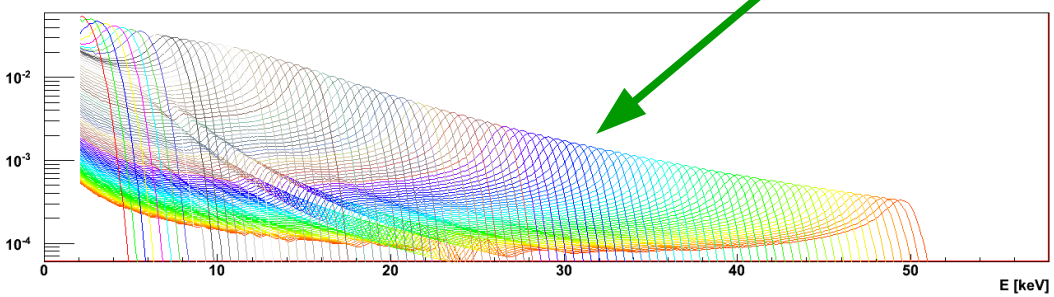
(measured)
source
spectrum

$$P(X|N) = \prod_{l\theta\, thr} \frac{N_{l\theta}^{thr\, X_{l\theta}^{thr}} e^{-N_{l\theta}^{thr}}}{X_{l\theta}^{thr}\,!}$$

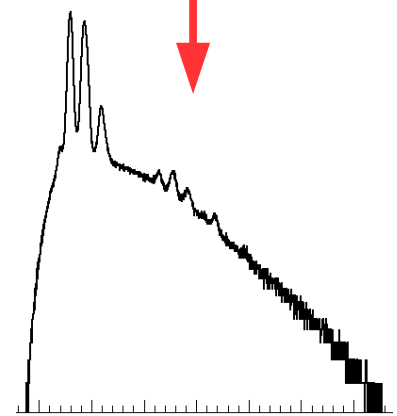
$$N_{l\theta}^{thr} = \int_{E_l^{thr}}^{\infty} dE \int_0^{\infty} dE' \, R(E;E') \, S_0(E) \, e^{-\sum_n \rho_n \frac{\mu_n}{\rho_n}(E) \int_{l\theta} f_n(x) dx}$$

(unknown)
Vector image

(known)
absorption
coefficients
+
(nominal)
densities



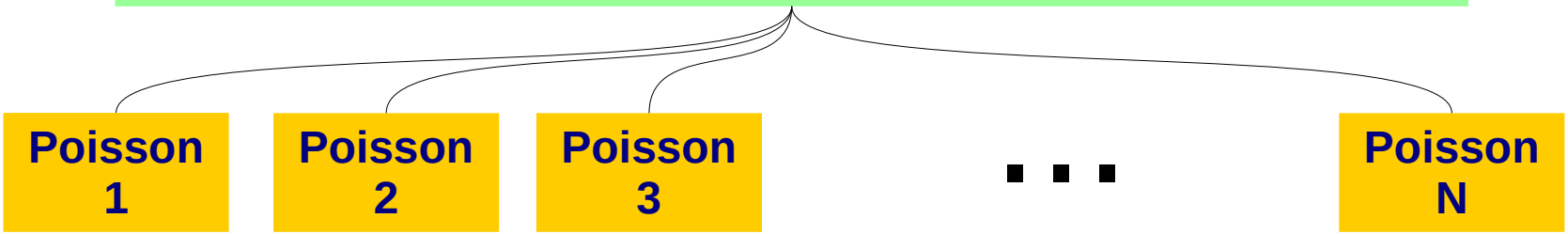
(measured)
Detector response function



(measured)
source
spectrum

$$f_n(x) = argmax\, P(X|N) = argmax \prod_{l\theta thr} \frac{N_{l\theta}^{thr\, X_{l\theta}^{thr}} e^{-N_{l\theta}^{thr}}}{X_{l\theta}^{thr}!}$$

Probability density function



Probability density function

Poisson 1 | Poisson 2 | Poisson 3 | ... | Poisson N

$$N_{parameters} = N_{voxels}^{2} \times N_{materials}$$

$$N_{data} = N_{pixels} \times N_{angles} \times N_{thresholds}$$

Probability density function

Poisson 1 | Poisson 2 | Poisson 3 | … | Poisson N

30000 | 100^2 | 3

$$N_{parameters} = N_{voxels}^{2} \times N_{materials}$$

54000 | 100 | 180 | 3

$$N_{data} = N_{pixels} \times N_{angles} \times N_{thresholds}$$

```
enricojr@enricojr-Vostro-3350 ~ $
enricojr@enricojr-Vostro-3350 ~ $ root -l
root [0] using namespace RooFit

RooFit v3.59 -- Developed by Wouter Verkerke and David Kirkby
                Copyright (C) 2000-2013 NIKHEF, University of California & Stanford University
                All rights reserved, please read http://roofit.sourceforge.net/license.txt

root [1] .q
enricojr@enricojr-Vostro-3350 ~ $
```

```
enricojr@enricojr-Vostro-3350 ~ $
enricojr@enricojr-Vostro-3350 ~ $ root -l
root [0] using namespace RooFit

RooFit v3.59 -- Developed by Wouter Verkerke and David Kirkby
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                All rights reserved, please read http://roofit.sourceforge.net/license.txt

root [1] .q
enricojr@enricojr-Vostro-3350 ~ $
```

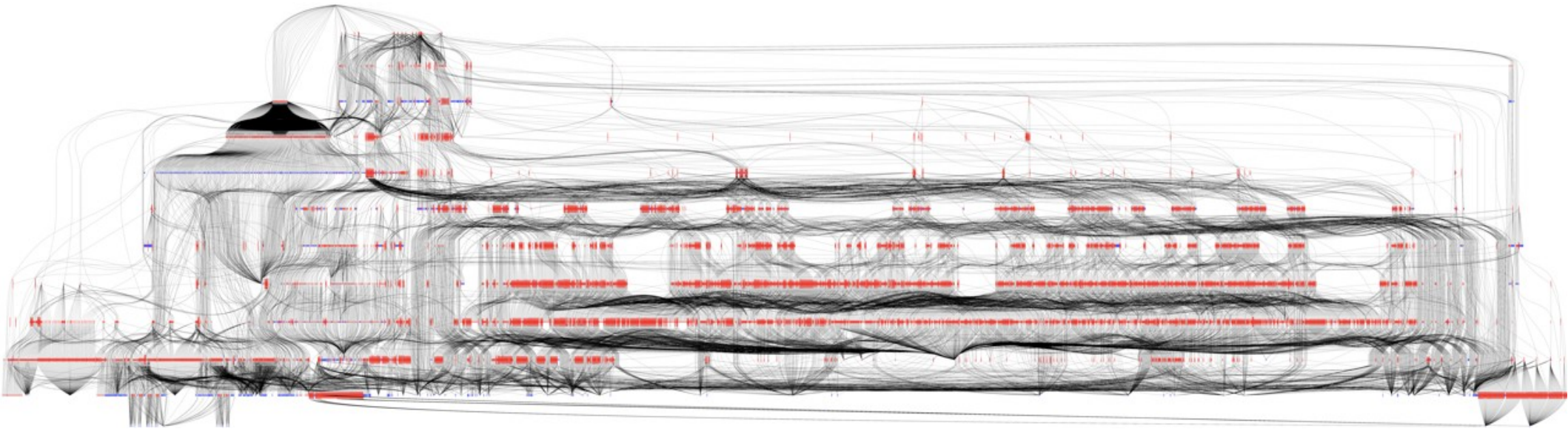

The full Higgs combination model, 23000 functions, 1600 parameters

Image credit http://cds.nyu.edu/projects/collaborative-statistical-modeling/

Nikhef

Science Park
Amsterdam
The Netherlands

W. Verkerke

me

Next steps:

- Optimize RooFit:
  - High energy physics → complex models, “few” parameters
  - Computed Tomography → “simple” models, many parameters
- Test on data
- Test on biological materials

WebSVN - ctreco - Rev 16 - / - Mozilla Firefox

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https://svnweb.cern.ch/cern/wsvn/ctreco

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(root)/ - Rev 16

Rev HEAD Go

Rev 15 | Last modification | Compare with Previous | View Log | RSS feed

LAST MODIFICATION

Rev 16 2015-02-16 19:00:43

Author: idarraga

Log message:

checking that the OB file exists and is not full of zeroes

Path	Last modification			Log	Download	RSS
demo/	3	32d 17h	schioppa	Log		RSS
libraries/	10	8d 08h	idarraga	Log		RSS
compile	3	32d 17h	schioppa	Log		RSS
drawImages.C	3	32d 17h	schioppa	Log		RSS
filterImage.cc	3	32d 17h	schioppa	Log		RSS
interpolateBadPixels.cc	16	7d 21h	idarraga	Log		RSS
Makefile	8	9d 00h	idarraga	Log		RSS
makeSinogram.cc	6	31d 19h	idarraga	Log		RSS
normalizeToOB.cc	3	32d 17h	schioppa	Log		RSS
plotSinogram.C	3	32d 17h	schioppa	Log		RSS
prepareRun.sh	15	7d 22h	idarraga	Log		RSS
README.txt	2	32d 18h	idarraga	Log		RSS
reconstruct_FBP.cc	6	31d 19h	idarraga	Log		RSS
reconstruct_OSEM.cc	13	7d 22h	idarraga	Log		RSS
sumFramesWithFormat.cc	3	32d 17h	schioppa	Log		RSS

Compare Paths

Menu WebSVN - ctreco - ... Home 77.0°C 100% feb 24, 4:09

Summary: the 5 rules

RULE #1: ENERGY (COLOR) = MATERIAL

RULE #2: NEED TO GO 

RULE #3: NEED TO MEASURE ENERGY

RULE #4: #materials = #thresholds

RULE #5: NEW RECONSTR. ALGORITHM